Analysis of Levitational Systems for a Superconducting Launch Ring*

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ABSTRACT

The launch ring consists of a maglev system in which a levitated vehicle is accelerated in an evacuated circular tunnel until it reaches a desired velocity and then releases a projectile into a path leading to the atmosphere. This paper analyses several levitational concepts for a system that employs superconductors in the stator and on the vehicle. Both an attractive and a shear-force configuration are shown to offer static stability over the velocity range from 0 to 10 km/s.

I. INTRODUCTION

So far, the chemical rocket has been the only technology that mankind has successfully used to move people and material from the Earth's surface into low-earth orbit and beyond. The cost of this technology, even with partially reusable rockets, has remained sufficiently high that its use has remained limited. There is general acceptance that a lower cost alternative to rockets would greatly increase the volume of traffic to space.

A. Alternatives to Rockets

The space elevator [1-3] is probably the best-known proposed alternative technology to rockets. The usual contemporary design concept for a space elevator is based around a mechanical cable extending radially inward and outward from a geosynchronous orbit, usually with a counterweight at the outer radius and with the innermost part of the cable attached to the ground at the equator. An elevator car can then attach to the cable and ferry people or material up or down. Unfortunately, currently available materials are not strong enough to support their own weight in a constant-cross-sectional-area cable from an earth geosynchronous location to the earth's surface. In principle, such a cable can be constructed by tapering the cross section from a small diameter at the ends to a very thick diameter at the geosynchronous point [2]. In practice, the strength of presently available engineering materials makes the mass of such a cable uncomfortably large. Other types of proposed space-elevator concepts that could provide access to low Earth orbit include a high-Jc superconducting cable that can self-levitate in the Earth's magnetic field [4, 5] and a massive ring rotating in a vertical plane such that the centrifugal force of the ring counters the gravitational force in the upper part of the orbit [6].

Another generic type of alternative consists of accelerating a projectile to high velocity at the Earth's surface. These "gun" concepts include railgun, coilgun, electrothermal-chemical gun, light-gas gun, RAM accelerator, and blast-wave accelerator [7]. Most gun concepts involve short acceleration times, and the subsequent large power supplies to boost even modest masses to the required velocity are likely to be expensive. Electromagnetic launch has been proposed to give rockets an initial velocity component, with most of the required velocity provided by combustion of the propellant [8]. Ground-based, high-powered lasers that augment the chemical energy of rocket propellant will also likely require large power supplies [7].

B. The Launch-Ring Concept

The launch-ring concept, shown in Fig. 1, consists of a maglev carriage accelerated by a linear motor around an enclosed, horizontal, evacuated circular track of large ring diameter. Magnetic forces in opposition to radial acceleration prevent the carriage from contacting the passage wall, and the carriage is statically stable in vertical, radial, yaw, pitch, and tilt directions due to the action of the levitation system. A projectile is clamped into the carriage until it reaches launch speed whereupon the projectile is released into a tangential launch ramp, through an egress hatch and potentially into orbit. Unlike, most of the other gun concepts, acceleration in the launch ring occurs over a relatively large time, and the required power supply is much more modest. The launch ring has some general analogies to the slingatron [9], but differing greatly in that the acceleration tube of the launch ring remains stationary.

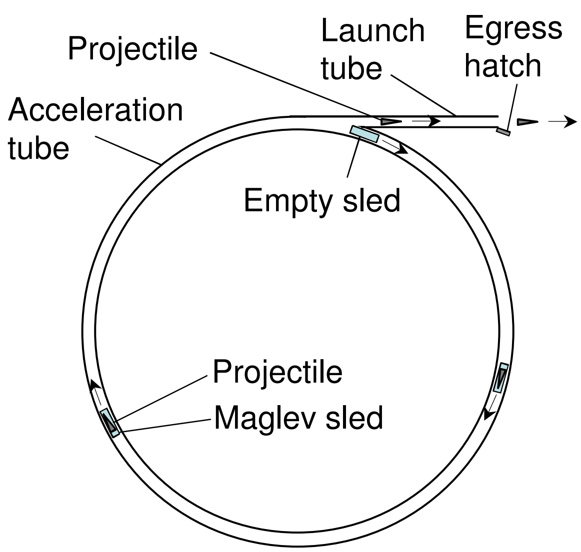

Fig. 1. General launch-ring concept.

While many technologies need to be integrated to develop the launch-ring concept, this paper is limited to a discussion of the levitation system and the stability of the sled. The discussion is further limited to two specific design geometries that provide static stability through the entire range of sled velocities from zero to 10 km/s and produce a minimal amount of heat in the acceleration tube.

We consider the stator of the levitation system to consist of several circumferential cables composed of superconducting NbTi. The stator is cooled at either 4.2 K or 1.9 K, using technology developed for particle accelerator magnets. In the designs analyzed, the stator current is constant throughout the period of sled acceleration. Superconducting coils on the vehicle consist of Nb3Sn and are cooled in the field of the stator. The heat capacity of the vehicle coils keeps them superconducting for the duration of the acceleration within the ring. Because the vehicle coils are persistent-current superconductors, a change of external flux threading one of the coils will induce a change of current in it. The position and orientation of the vehicle in the magnetic field of the stator, as well as mutual inductance between the vehicle coils, affect the currents in each coil. As the vehicle is accelerated and changes its position in the magnetic field of the stator, current is induced in the vehicle coils.

II. MODEL DESCRIPTION

The magnetic forces are calculated by treating individual cable segments as filaments. The radius of the acceleration tube is expected to be of the order of a kilometer, whereas the size of the vehicle is of the order of a meter. We therefore assume that the forces and stability can be calculated by treating the stator as a set of infinitely long filaments.

For a single infinitely long filament with current I_S, the vector magnetic field **B** at a perpendicular distance ρ from the filament is

$$\mathbf{B} = [\mu_0 I_S / (2\pi\rho)]\ \mathbf{b} \qquad (1)$$

where $\mu_0 = 4\pi \text{x} 10^{-7}$ N/A^2, and **b** is a unit vector in the azimuthal direction perpendicular to the radial direction from the filament to the point in space, with orientation given by the right-hand rule according to the current direction.

Mutual inductance, $M_{k,m}$, between a pair of vehicle coils k and m, is calculated by assuming 1 A of current in one of the coils, calculating the magnetic field from each of four coil segments and integrating over the area of the other coil to determine the total flux threading it. To calculate the magnetic field from a finite filament, we use the method of Hanson and Hirshman [10]. Self inductance L for each vehicle coil of length L_v and width W_v is calculated from

$$L = [\mu_0/(2\pi)]\ P\ [\log_e(2P/d) - a + 1/4] \qquad (2)$$

where the self inductance is in henries, the coil perimeter is $P = 2L_v + 2W_v$ in m, d is the wire diameter in m, and a is a parameter that depends on L_v/W_v and is given in Table 8 on p. 61 of Grover [11]. L becomes infinite with infinitesimal filament diameter, so we will have to use an actual diameter to get a number here and chose $d = 0.01$ m for all the calculations.

The vehicle contains n coils. The relationship between the change in current ΔI_m in coil m with the change in external flux $\Delta\Phi\text{ext}_m$ through coil m is represented by the following set of simultaneous equations.

$$\sum_{k=1}^{n} M_{m,k}\ \Delta I_k = -\Delta\Phi\text{ext}_m \qquad (3)$$

where $M_{k,k} = L_k$. Each vehicle coil is modeled as four filaments that form a rectangle and carry current I_V. The total flux Φ threading a coil is calculated by dividing the area formed by the four coil filaments into surface elements and integrating the external magnetic field normal to each surface element over the entire surface. The force on each filament is calculated by dividing the filament into small elements of length d**l**, and using

$$d\mathbf{F} = I_V \, d\mathbf{l} \times \mathbf{B}_{ext} \qquad (4)$$

and the d**F**s are summed to get the force on each filament, and the forces on all the filaments summed to get the total force on the vehicle. Torques are similarly calculated from the torque contribution on each element, given by

$$d\boldsymbol{\tau} = \mathbf{r} \times d\mathbf{F} \qquad (5)$$

where **r** is the vector from the center of the vehicle to the filamentary element.

In addition to vertical and horizontal displacements, the vehicle may undergo: Yaw = α, a rotation of the coil in the yz plane; Pitch = β, a rotation of the coil in the xy plane; Roll = γ, a rotation of the coil in the xz plane. In the stability analysis, we assume that these angles are small and that calculations need only be carried to first order.

III. ATTRACTIVE LEVITATION

In the attractive levitation scheme, the stator consists of a set of NbTi rings, separated vertically, with most located inward from the vehicle. The coils on the vehicle are field cooled at a location close to the stator. As the vehicle accelerates, it moves radially outward, decreasing the magnetic flux and increasing the current in the vehicle coils such that there is an attractive force between the stator and the vehicle. The initial position is chosen to allow cryogenic containment and mechanical support structure around both the stator and the vehicle superconductors, assuming that the filaments have a cross sectional area compatible with a current density of 100 kA/cm2.

Figure 2 shows one of the geometries used to model the system, which provided the largest levitational force of the attractive systems modeled. The stator consists of 6 parallel wires, infinitely long in the y direction, with the same current I_S, 4 in the positive y direction and 2 in the negative y direction. Analysis showed that a single-coil vehicle geometry, and vehicle geometries with two coils either separated vertically or in the y direction, were unstable to one or more of the angular disturbances. Complete stability was obtained in a four-coil geometry, with a coil occupying a corner of a rectangle residing in the yz plane.

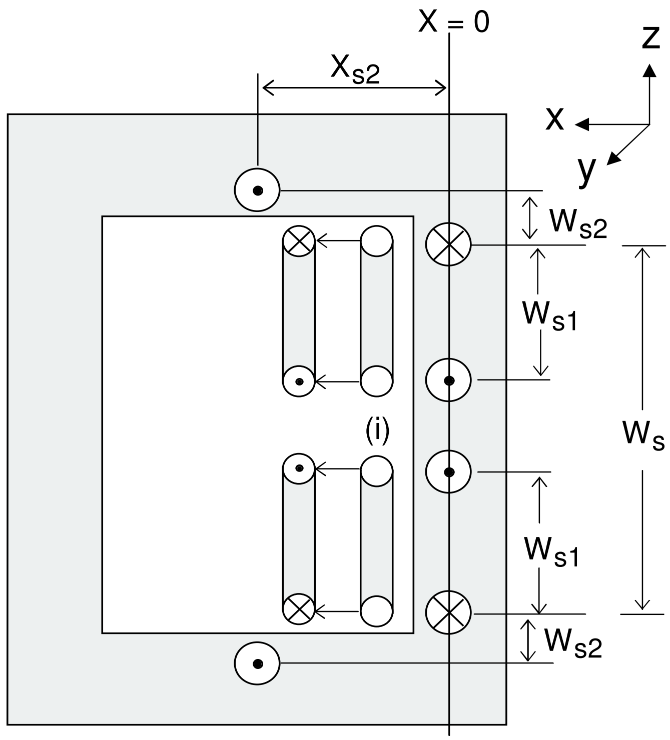

Fig. 2. Attractive-force levitation geometry, showing six stator filaments (in shaded block) and two (of four) vehicle coils that are initially (i) without current but develop current as the vehicle moves outward.

Stator geometries were also modeled that consisted of a pair of filaments separated in the z-direction, and four filaments in the same vertical plane. In both cases, the filaments were all inward from the vehicle and four coils were required on the vehicle for stability.

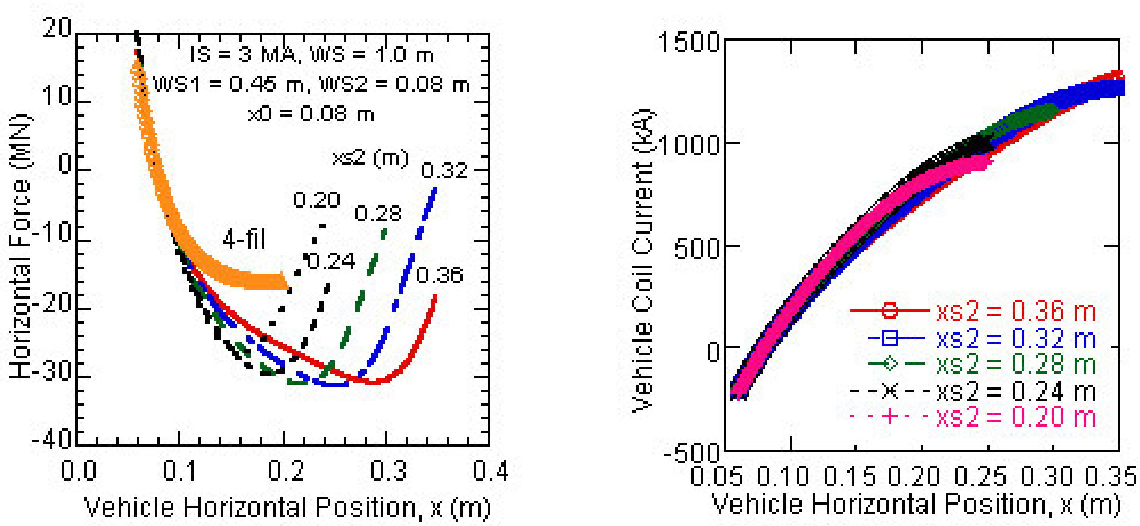

Fig. 3. Horizontal force and vehicle coil currents as a function of vehicle horizontal position for different xs2 in an attractive-levitational configuration.

In Fig. 3a, we see that, compared to the 4-filament stator, by adding 50% more amp-turns to the stator, we have doubled the force. Comparing all of the curves, there appears to be a maximum force that occurs for xs2 = 0.28 m. The vehicle coil current is mostly independent of xs2, indicating that this is largely controlled by the four stators at x=0. For reference, a 100-kg vehicle moving in a radius of 1-km at a velocity of 10 km/s requires a 10 MN radial force for equilibrium.

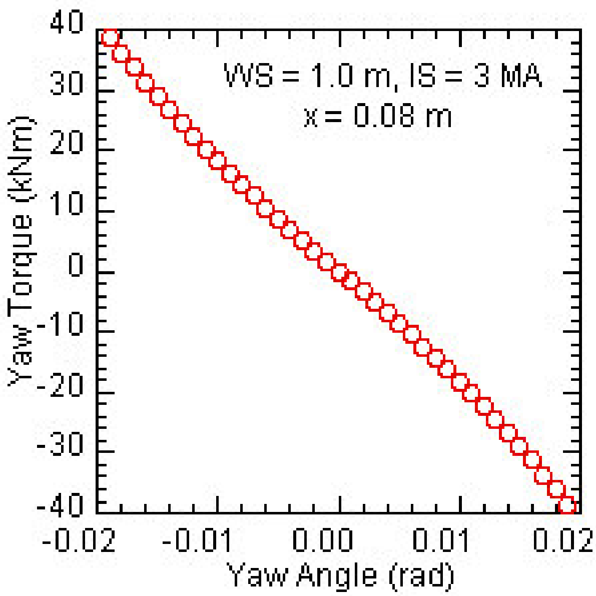

Fig. 4. Yaw torque versus yaw angle at initial horizontal.

Stability of the system is determined by calculating the force in the direction of motion as the vehicle is perturbed in that direction. An example is shown in Fig. 4, were yaw torque is shown versus yaw angle. Because the force is restoring against the perturbation, the system is stable to perturbations in this direction. A set of these graphs, consisting of perturbations for yaw, pitch, roll, and vertical displacement were obtained at various horizontal displacements to assure that the system was stable. In all cases, the deflection in the vertical direction due to Earth's gravity was found to be negligible.

IV. SHEAR-FORCE LEVITATION

Figure 5 shows the basic geometry for a shear-force configuration. The advantage of this geometry is that the magnetic field is approximately the same over the entire horizontal traverse of the vehicle and that it is easier to mechanically confine the stator filaments. The vehicle has four coils: two on the top, front and back; and two on the bottom, front and back. The stator consists of 6 filaments: 3 on top and 3 on the bottom, with the same current I_S. The top and bottom trios are separated by W_S in the z direction. The filaments are separated by Hv in the x direction. The vehicle coils are oriented nominally in the xy plane and traveling in the y direction, with width H_V in the x direction and length L_C in the y direction. The separation between the top and bottom pairs of vehicle coils is Wv, Each coil is a single filament with current $I_{V,m}$, (m = 1-4)

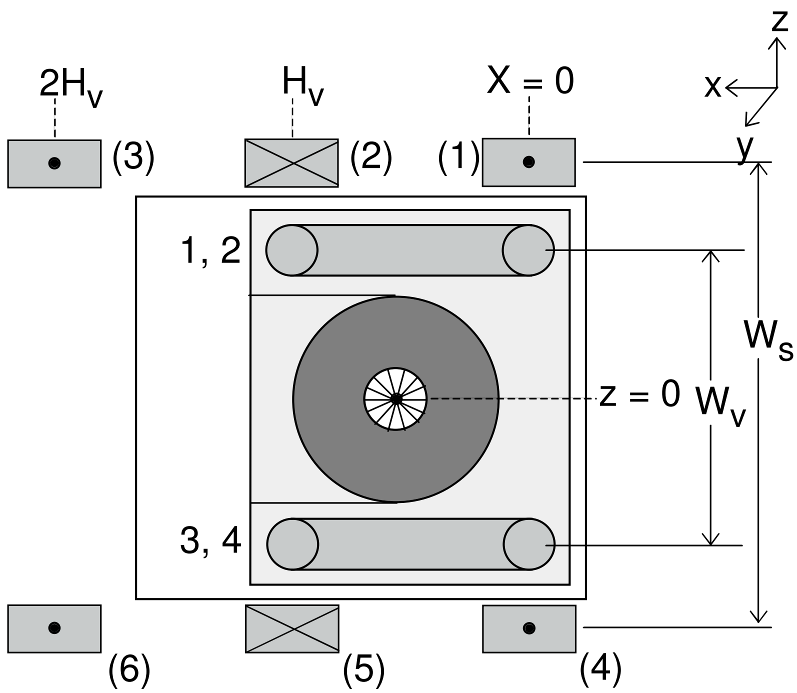

Fig. 5. Shear force levitation geometry.

In the example shown in this paper, $W_S = 1.0$ m, $Wv = 0.90$ m, and $Hv = 0.45$ m. Figure 6 shows the horizontal force and vehicle coil current as a function of vehicle horizontal position. Using 6 filaments for the stator, in the shear-force geometry with 2 MA in each stator filament, 40 MN of force can be exerted on the vehicle, whereas in the attractive-force geometry, 3 MA per stator filament was necessary to obtain 30 MN of force.

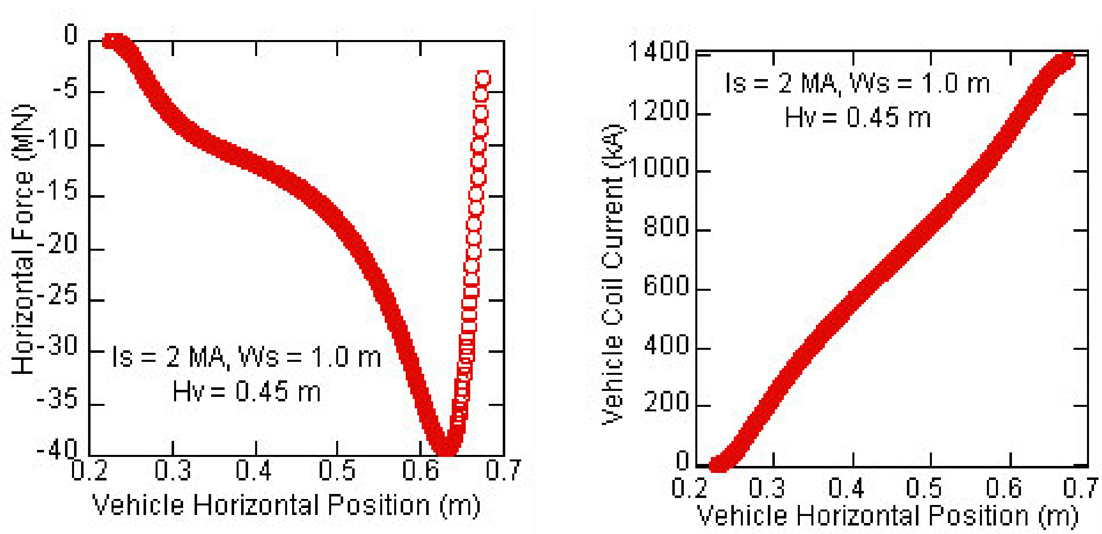

Fig. 6. Horizontal force and vehicle coil current as a function of vehicle horizontal displacement in a shear-force geometry configuration.

V. SCALING LAWS

The force on the vehicle is proportional to the magnetic field of the stator times the current in the vehicle coils. Because the current in the vehicle coils is induced by changes in position, it is proportional to the magnetic field. Therefore, the force is proportional to the square of the stator current. Independently, the force is inversely proportional to the acceleration tube radius. The stator superconductor is a major cost component of the system, assumed to be roughly proportional to the ampere-turns of the stator. This cost is then inversely proportional to the stator current, or proportional to the square root of the radius of the launch ring. In practice, the stator current will be limited by the self critical field at its outer conductor radius. Trying to increase the stator current by decreasing the stator current density would increase the separation distance between vehicle and stator and reduce the force.

VI. DISCUSSION

This paper has examined two levitational configurations for the launch-ring concept that are capable of providing stability over the entire range of velocities from stationary to 10 km/s. Other technical design issues would need to be addressed before a viable design concept could be proposed for launching projectiles. These issues include acceleration of the vehicle within the acceleration tube in a manner compatible with the levitational approach, heating and stability of the stator from the magnetic pulse as the vehicle passes, heating of the vehicle coils over time, a means to control the direction of egress of the projectile from the launch-tube exit, and survival of the projectile through the Earth's atmosphere. These issues are beyond the scope of the present paper.

CONCLUSIONS

In attractive-force and shear-force configurations, four vehicle coils are required to simultaneously provide stability in the radial, vertical, yaw, pitch, and roll directions over the entire range of velocities from 0 to 10 km/s. For a given amount of ampere-turns of stator, the shear-force levitation geometry provides a larger force than the corresponding attractive-force geometry.

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