THE NASA INDUCTRACK MODEL ROCKET LAUNCHER AT THE LAWRENCE LIVERMORE NATIONAL LABORATORY*

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SUMMARY

The Inductrack magnetic levitation system, developed at the Lawrence Livermore National Laboratory, is being studied for its possible use for launching rockets. Under NASA sponsorship, a small model system is being constructed at the Laboratory to pursue key technical aspects of this proposed application. The Inductrack is a passive magnetic levitation system employing special arrays of high-field permanent magnets (Halbach arrays) on the levitating carrier, moving above a "track" consisting of a close-packed array of shorted coils with which are interleaved with special drive coils. Halbach arrays produce a strong spatially periodic magnetic field on the front surface of the arrays, while canceling the field on their back surface. Relative motion between the Halbach arrays and the track coils induces currents in those coils. These currents levitate the carrier cart by interacting with the horizontal component of the magnetic field. Pulsed currents in the drive coils, synchronized with the motion of the carrier, interact with the vertical component of the magnetic field to provide acceleration forces. Motional stability, including resistance to both vertical and lateral aerodynamic forces, is provided by having Halbach arrays that interact with both the upper and the lower sides of the track coils. In its completed form the model system that is under construction will have a track approximately 100 meters in length along which the carrier cart will be propelled up to peak speeds of Mach 0.4 to 0.5 before being decelerated. Preliminary studies of the parameters of a full-scale system have also been made. These studies address the problems of scale-up, including means to simplify the track construction and to reduce the cost of the pulsed-power systems needed for propulsion.

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INTRODUCTION

The Inductrack concept uses passive magnetic levitation that is generated when a moving object holding an array of permanent magnets moves over shorted loops of wire embedded in a stationary track (ref. 1). The interaction of the magnetic field moving over the wires induces currents in the wire. Above a critical speed, the induced current interacts with the magnetic field to generate a repulsive force that levitates the object above the track. There are many potential applications of this concept that range from magnetic bearings in motors to levitating a cradle that carries a payload or a trainload of people. In particular, under NASA sponsorship at Lawrence Livermore National Laboratory, we are building a prototype to demonstrate the feasibility of this concept for initiating rocket launches. At this phase of the project, our goal is to demonstrate acceleration in excess of 10g's with stable levitation. (The high acceleration – higher than would be needed for magnetic launching – is dictated by our need to limit the track length and costs.)

The basic concept of passive magnetic levitation has already been demonstrated at LLNL (ref. 2). In that experiment, a 20-kg cart was accelerated (at about 1 g) to 12 m/s, a speed which was about 6 times greater than the critical speed needed for levitation. Following initial acceleration, the cradle entered the region of shorted coils, levitated, and coasted to a stop on its auxiliary wheels at the end of the 20-m track. Except for initial transients, which damped out in flight, the cradle behaved stably.

THEORY

Levitation

The Inductrack concept for passive magnetic levitation uses a special configuration of high strength permanent magnets. This configuration, called a Halbach array, has an array of permanent magnets with a direction of magnetization that is rotated by 90° with respect to adjacent magnets (ref. 3). Figure 1 shows the contours of constant magnetic flux around a 5-bar array that is similar to that used in the Inductrack experiment. Without the horizontally-polarized magnets, the flux would be equal on the top and bottom.

An infinite number of bar magnets in a Halbach configuration would produce a sinusoidal variation of field at a constant distance from the bottom of the array. For the five magnets, the field parallel to the bottom of the array (B_x) and the field normal to the bottom of the array (B_y) are nearly sinusoidal in the x direction, parallel to the bottom of the array. Figure 2 shows these field profiles as generated using ANSYS (ref. 4) for our array that is 1-cm thick, 13-cm (5 bars) wide, and 12-cm long. The remanent field of these magnets, composed of NdFeB, is 1.23 T. The field is 0.26 T at 1-cm from the array surface, which is the expected levitation height above the shorted coils.

The sinusoidal variation in $B_x(x)$ and $B_y(x)$ is critical to provide the proper time-variation in magnetic field experienced by the stationary wires as the magnets move by. As the field cuts through the nearest upper conductors in the track, the time-variation in magnetic field acts as a voltage source in each closed loop of wire. The effective circuit of this wire is just an inductor L and resistor R in series so that the levitation forces can be predicted through standard circuit theory. The excitation frequency ω of the circuit is $\omega = k\ v$ where $k = 2\pi / \lambda$, v is the array velocity (m/s), and λ is the array wavelength (0.1-m as seen in figure 2). When $\omega >> R/L$ the phase of the current is shifted 90° with respect to the voltage so that the current is in phase with the flux which maximizes the force in the $+y$ direction to provide lift and minimizes the drag force. For velocities much greater than the transition speed of

$$v_t = (\lambda R)/(2 \pi L) \text{ m/s}, \qquad (1)$$

the cradle will lift off the track. For lesser velocities, the drag force, acting in the $-x$ direction, will decelerate the cradle. At a speed of v_t, the levitation and drag forces are equal.

The current I_L induced in each closed loop is a function of the flux ϕ enclosed so that

$$I_L = \phi / L = \lambda B_0/(2 \pi L)\, w \exp(-2\, k\, y_1) \sin(k\, x) \text{ A} \qquad (2)$$

where B_0 is the theoretical surface field for a Halbach array, w = length of the excited wire and y_1 = gap between the array and wire. This surface field, as given by Halbach, is

$$B_0 = B_r\,(1 - \exp(-k\, d)) \sin(\pi /M)/(\pi /M) \text{ T} \qquad (3)$$

where d = array thickness and M = the number of magnets per wavelength (4 in the present case). The levitating force, averaged over x, is produced when the induced current is crossed with B_x so that the average levitating force per closed loop is

$$< F_y > = <B_x(x)\, w\, I_L> \text{ N}. \qquad (4)$$

The theory and assumptions behind equations 1-4 can be found in other articles (refs. 1, 2).

Acceleration

Acceleration is provided to the cradle through the use of an impulsive current provided to drive coils that turn on when the peak of the B_y field is present (refer to figure 2). Because the drive loop generates a local field that could affect the induced current in the nearby levitation coils, there is also a flux-canceling coil that is co-planar with the drive coil. The wire layout is configured so that the return path for current is far from the magnets yet creates a flux pattern that yields a zero net flux in the adjacent circuits.

The peak value of acceleration can be estimated from the peak strength of B_y so that

$$B_{y,max} = B_0 \exp(-k\,(y + d_c/2)) \text{ T} \qquad (5)$$

where d_c is the conductor thickness. Then the peak force F_x, dependent on the drive current I_D is given by

$$F_x = B_{y,max}\, w\, I_D \quad \text{N}. \tag{6}$$

Experiment

Mechanical

In the present phase of development, the Inductrack test track is 30-m long. Mechanical acceleration, e.g. a compressed air cylinder, will be used to launch the cradle. This should provide acceleration to 10 m/s within the first meter. Mechanical acceleration is considerably less expensive than electrical drive during this launch phase. The next 16 meters is the acceleration/levitation section of track. Here the drive coils are interleaved with the levitation coils every 5 cm. The levitation coils are 1-cm wide and the levitation coils are 4-cm wide. The remaining track length has a non-magnetic stainless steel sheet that provides deceleration caused by the eddy currents in the conducting sheet that are generated when the magnets move by.

The cradle, pictured in figure 3, is composed of carbon-fiber composite material and has a length of 64 cm. A 3d ANSYS (ref. 4) computer simulation aided in the development of this design. The analysis was used to minimize the weight yet withstand 40 g's of acceleration. It was also used to design the structure necessary to keep the cradle from "opening" due to the repulsion of the magnets away from the track and to calculate the natural frequencies of the cradle structure. The cradle has arms that extend past the track and surround the guide rails. As seen in the photo of the Inductrack model in figure 4, the C-guides on these arms are needed to prevent the track from touching the fragile magnets on the inside of the cradle prior to levitation. The cradle without the magnets weighs 3 kg.

There are three arrays of magnets on the front and three on the back of the cradle. These magnets are located next to the track inside the cradle ribs as pointed out in figures 3 and 4. The lower magnets oppose the force in the upper magnets. The upper magnets have a width of 12-cm and the lower a width of 8-cm. Because the lower magnets are at a 45° angle to the upper magnets, only 6% of the repulsive force from the top magnets balances the weight of the cradle and magnets. The remainder is used to center the cradle about the track to provide stability. The total weight of the cradle and magnets is 8.5 kg.

Electrical

Within each set of levitation coils, which are 4-cm wide, are close-packed loops of #10 wire. The perimeter of each loop is 56-cm. Each loop has a resistance of $1.5 \times 10^{-3}\ \Omega$ and inductance of 2.6×10^{-6} H. Applying these values to equation 1, one finds the transition speed for our levitation coils is 11 m/s. Thus mechanical acceleration produces levitation just after the first meter of track.

The NdFeB magnets with a $B_r = 1.2$ T have a thickness d of 1-cm and $M = 4$ magnets per wavelength (as seen in figure 2). According to equation 3 then the field at the surface (if the array were infinitely long) would be $B_0 = 0.52$ T. We anticipate that the cradle will levitate at $y_1 = 1$ cm above the track. We also assume that the lateral arrays will levitate at 1-cm above the track. Thus, using equation 2, one finds that the current generated in each loop by the presence of the three, moving Halbach arrays, that have a total length of $w = 12+2*8$ cm, is 570 A. The total repulsive force provided by just the top array is 1450 N. With 94% of this force contributing to stability, the remaining lifting force provided by all six arrays is 166 N. This should provide sufficient lift with some operating margin for the 8.5-kg cradle assembly.

The drive coils comprise a single turn of # 6 square insulated magnet wire. The drive coils are separated by 5-cm to align with the peaks in $B_y(x)$ seen in figure 2. Note that because $B_y(x)$ changes sign, the current pulse must also switch directions to still produce a forward force. Thus six drive coils (3 front and 3 back) are energized simultaneously to provide acceleration. A pulse of 7000 A with a fixed width of 600 micro-seconds is expected to produce a maximum cradle speed of around 50 m/s at the end of the driven section of the track. Using equations 5 and 6, one can estimate that the maximum acceleration will be about 3000 N or 36 g's. Although a variable pulse width could provide optimal acceleration in a shorter distance, this option is very expensive because of the number of high current switches required.

The drive circuitry is triggered pairs of infrared detector/emitters mounted along the track. The infrared beam sends a trigger signal when an arm attached to the cradle blocks the beam. This signal will also be used as a diagnostic to measure cradle velocity. A series invertor is used as an ac switch for each group of drive coils. When triggered, the series invertor both energizes the desired group of coils and creates the half-sine wave pulse of fixed amplitude and time. The pulse width and amplitude depend on the inductance and resistance of the coils, the capacitance of the resonant capacitor, and the dc bus voltage. The pulse width can be varied in discrete intervals along the track by changing the value of the resonant capacitor.

FUTURE

The simplest diagnostic will be that of using the trigger signal to measure velocity. We also plan to add an on-board laser to project down the track in order to measure the pitch, roll, and yaw of the cradle. If necessary vibration dampers may also be added around the C-clamps to mitigate instabilities at the slower speeds. The next phase of this project is to extend the track to 100 meters in length and achieve peak speeds of Mach 0.4 to 0.5.

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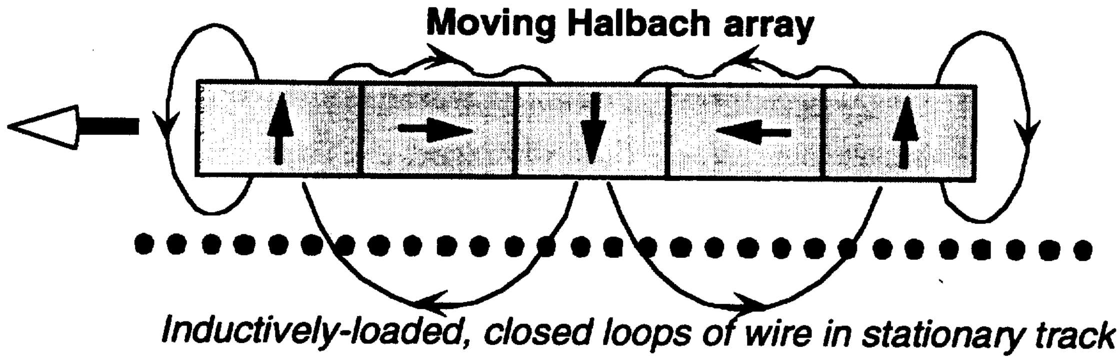

Figure 1. Sketch of passive magnetic levitation using a Halbach array of magnets. The horizontally-polarized magnets concentrate the flux on one side of the array and help to form the sinusoidal flux shape.

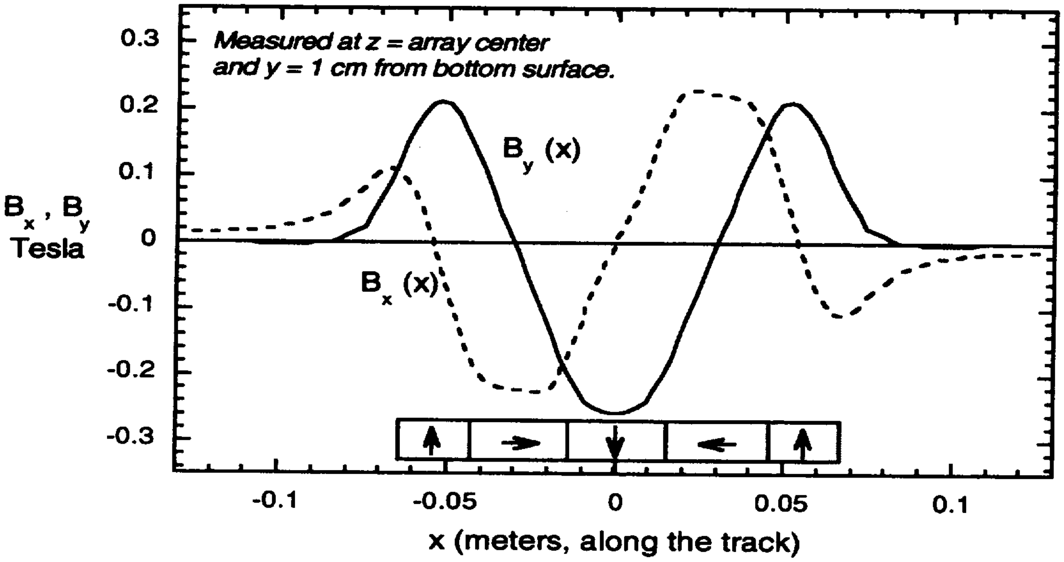

Figure 2. Variation of B_x and B_y along the track (in x) indicating the nearly sinusoidal behavior. Results are calculated from a 3d model of the Halbach array using ANSYS.

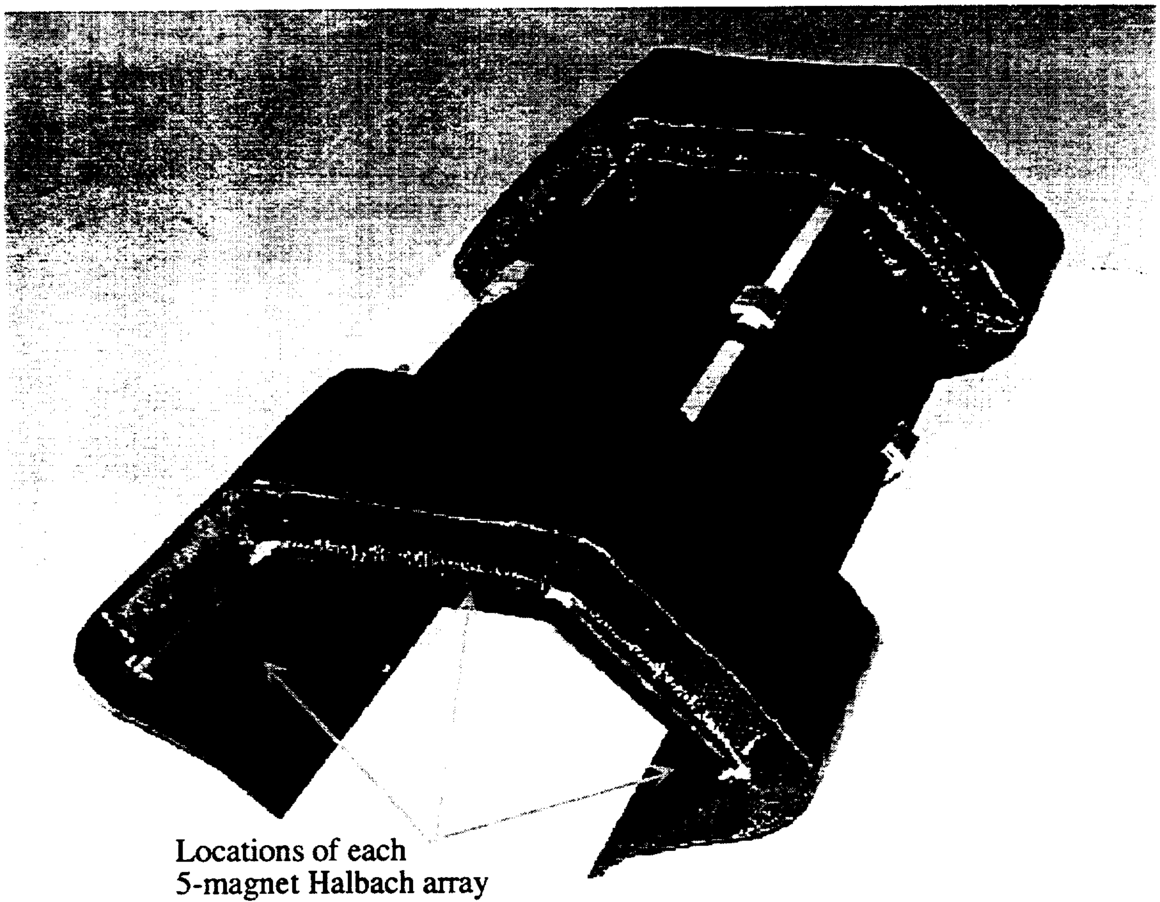

Figure 3. Photo of carbon fiber cradle (magnets not shown). The length is 64 cm.

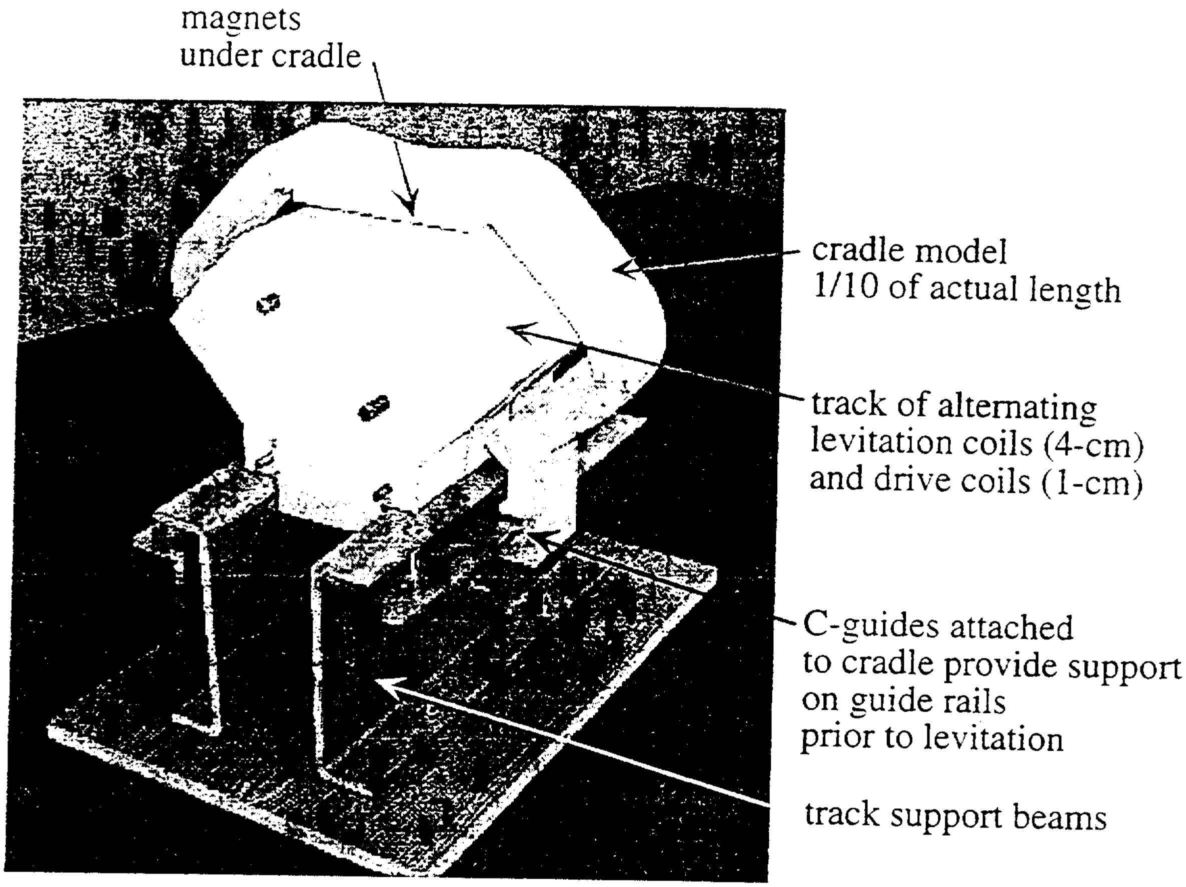

Figure 4. Photo of the model of the drive and levitation coil assembly.