

The Inductrack: A Simpler Approach to Magnetic Levitation

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Abstract

Arising out of research at the Lawrence Livermore National Laboratory on passive magnetic bearings, a new magnetic levitation system, the Inductrack, has been developed and tested at model scale. The system employs special arrays of permanent magnets (Halbach arrays) on the moving car. The magnetic field from the arrays induces repelling currents in a close-packed array of shorted circuits in the track. Above a low transition speed (a few kilometers per hour), levitation forces approach a constant value, while drag forces decrease inversely with speed, with L/D reaching 200:1 or more at operating speeds. The high magnetic efficiency of the Halbach arrays, plus the use of close-packed track circuits, results in levitating forces approaching 40 metric tons per square meter (using NdFeB permanent magnet arrays, whose weight in typical cases is a few percent of the levitated weight). The system is passively stable: only motion is required for levitation. Failure of the drive system only results in the train slowing down and settling onto auxiliary wheels at a low speed. A detailed theoretical analysis of the Inductrack was made, on the basis of which a small-scale model was constructed and operated. The laboratory is now building a new small-scale model system (under NASA sponsorship) to demonstrate the acceleration rates and speeds (1.0-g and Mach 0.4 in the model) needed to magnetically launch rockets.

1. Introduction

Magnetic levitation of high-speed trains has been a decades-long development in which many important advances have been made. Full-scale maglev systems have been demonstrated on test tracks in both Germany and Japan. Although these systems are marvels of modern engineering design and have achieved their design goals, commercially operating trains employing their design principles have yet to be put into operation. Among the reasons that the introduction of maglev systems has been slow to occur may be cost and complexity. For example, the German system employs servo-

controlled electromagnets, attracted upward to a track consisting of precisely aligned iron plates. Because of the small pole-to-track gap (of order 1 centimeter), and because such systems are inherently unstable (a consequence of Earnshaw's theorem¹), for reasons of safety the control system for the electromagnets must meet very demanding standards and must be highly redundant. The Japanese system, on the other hand, employs superconducting magnets on the train cars, with attendant control and cryogenic system requirements. The Inductrack concept² aims at finding a simpler and less expensive approach to maglev, one possibly with a wider variety of applications than present systems.

To achieve its levitating forces, the Inductrack employs a special array of permanent magnets (Halbach arrays) on the train car. When the train is in motion the magnetic field from these magnets induces repelling currents in a close-packed array of shorted conducting circuits in the "track." Figure 1 is a schematic representation of the Inductrack concept, showing a Halbach array moving above, and close to, the upper conductors of a close-packed array of shorted circuits. Also shown is the equivalent circuit of this system.

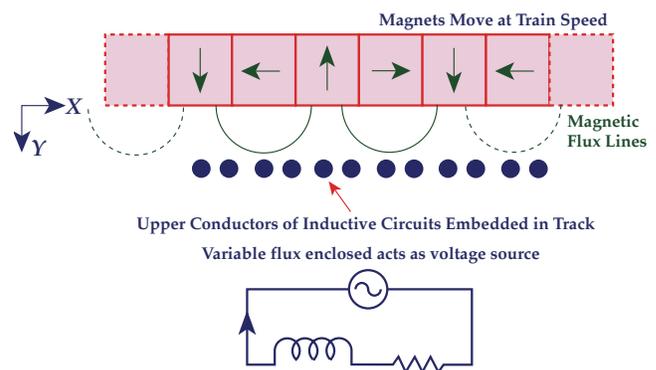


Figure 1 — Schematic diagram of Inductrack concept

In the past, the use of permanent magnets in maglev systems has been rejected for various reasons. One reason was that it was felt that they would not produce an adequate levitation force compared to the weight of the magnets themselves. In the Inductrack, this objection has been answered by the combination of two factors:

First, the Halbach array, as pioneered by Klaus Halbach for particle accelerator applications,³ represents the optimally efficient use of permanent-magnet material for creating a periodic magnetic field near the lower surface of the array. It accomplishes this result by canceling the field above the array, while producing a nearly purely sinusoidally varying periodic magnetic field below the array. Second, this periodic magnetic field couples strongly to the close-packed array of circuits that comprise the “track” of the Inductrack. As a result of these two optimizing design factors, it is not necessary to employ superconducting magnets in order to achieve adequate levitating forces.

Being an induction-activated, repelling-force, system, Earnshaw’s theorem does not apply to the Inductrack so that it requires no control circuits to achieve Earnshaw-stability. As long as the train is in motion (above a transition speed of a few kilometers per hour) it will be stably levitated. Failure of the drive system in the Inductrack would result in the train slowing down to low speed, then settling down on its auxiliary wheels prior to stopping.

The sections to follow summarize the results of our theoretical analyses of the Inductrack, describe the operating model that was built, and briefly discuss a new small-scale model system being constructed (under NASA sponsorship), aimed at a proof-of-principle of a proposed rocket-launching system.

2. Inductrack Theory

Analysis of levitation and drag forces of the Inductrack can be performed through standard circuit theory. The circuit equation relating the induced voltages and currents in the Inductrack is as follows:

$$V = L \frac{dI}{dt} + RI = \omega \phi_0 \cos(\omega t) \quad (1)$$

Here V is the induced voltage, I (amps) is the induced current, L (hy) is the inductance (self plus mutual) of a circuit, and R (ohms) is its resistance, and ϕ_0 (Tesla-m²) is the peak flux linked by the circuit. The steady-state solution of Equation (1) is:

$$I(t) = \frac{\phi_0}{L} \frac{\sin(\omega t) + \left(\frac{R \cos(\omega t)}{\omega L} \right)}{1 + \left(\frac{R}{\omega L} \right)^2} \quad (2)$$

The excitation frequency, ω , is determined by the wavelength of the Halbach array fields, λ (m), and the velocity, v (m/sec.), of the train, through the relation: $\omega = kv = (2\pi/\lambda)v$. As shown by Equation (2), in the limit $\omega \gg R/L$

the phase of the current is shifted 90° with respect to the voltage so that the current is in phase with the flux, maximizing the lifting force. The time-averaged lift and drag forces on each circuit are given by the expressions:

$$\langle F_y \rangle = \frac{B_0^2 w^2 \exp(-2ky_1)}{2kL \left[1 + \left(\frac{R}{\omega L} \right)^2 \right]} \text{ Newtons} \quad (3)$$

$$\langle F_x \rangle = \frac{B_0^2 w^2 \left(\frac{R}{\omega L} \right) \exp(-2ky_1)}{2kL \left[1 + \left(\frac{R}{\omega L} \right)^2 \right]} \text{ Newtons} \quad (4)$$

Here w (m) is the transverse width of the Halbach array, and y_1 (m) is the vertical distance between the lower surface of the Halbach array and the centroid of the upper leg of the circuit (for circuits in the form of a close-packed array of rectangles, resembling window frames). The quantity B_0 is the peak field at the surface of the Halbach array.² For NdFeB magnets it is typically approximately equal to 1.0 Tesla.

Dividing Equation (3) by Equation(4) gives the lift-to-drag ratio:

$$\frac{\text{Lift}}{\text{Drag}} = \frac{\omega L}{R} = \frac{2\pi v}{\lambda} \left[\frac{L}{R} \right] \quad (5)$$

Note that the L/D ratio increases monotonically with the velocity, the drag varying inversely with velocity. This situation contrasts with that for aerodynamic drag or wheel-rail friction, both of which increase with velocity. For typical track parameters, L/D can approach 200:1 at train operating speeds, to be contrasted with typical values for jet aircraft of 25:1.

One alternative simple form that the Inductrack might take is that of a laminated stack of thin anodized aluminum sheets, each of which has narrow transverse slots terminating at each side to leave conducting edges. (Lamination reduces residual eddy-current losses). For this case the inductance term, L , is given by the expression:

$$L = \frac{\mu_0 w}{2kd_c} \text{ hy} \quad (6)$$

Here $\mu_0 = 4\pi \times 10^{-7}$ hy/meter, and d_c (m) is the center-to-center spacing of the conducting strips between the slots. For this case the levitating force per square meter of Halbach army, obtained by inserting Equation (6) in Equation (3) and summing over area, is given by the expression:

$$\frac{\sum \langle F_y \rangle}{Area} = \frac{B_0^2}{\mu_0} \exp(-2ky_1) \text{ Newtons/m}^2 \quad (7)$$

Note that this force per unit area is twice as large as one would intuitively guess from the strength of the magnetic field of the Halbach array. The factor of two increase comes from the “image effect” of the close-packed circuits. This effect doubles the local field (a factor of four increase in force).

Then, the mean-square value of B_0^2 , being one half of its peak value, yields a net factor of two increase. Inserting 1.0 Tesla for B_0 and evaluating Equation (7) at the surface of the Halbach array ($y_1 = 0$) one finds for the maximum levitation capacity per unit area a value of about 80 metric tons per square meter. Thus, taking the usable levitating force at one-half its maximum, for example, up to 40 metric tons/m² might be achieved in such systems. When the flat-plate-type of track is replaced by the window-frame type, the force is reduced in the ratio of $\tau w/P_c$, where P_c (m) is the perimeter of the circuit.

Another useful design quantity is the transition velocity, defined as the velocity at which the lifting force has reached one half of its asymptotic value (also the same velocity at which the lift and drag forces are equal). We first define, from Equation (5), the parameter, K (Newtons/Watt), given by the expression:

$$K = \frac{2\pi}{\lambda} \left[\frac{L}{R} \right] \text{ Newtons/Watt} \quad (8)$$

The parameter K measures the levitation efficiency of the system. For circuits with no added inductive loading, typical values of K are of order 1.0 N/W, corresponding to a power requirement of order 10k W to levitate 1.0 metric ton. Adding inductive loading will increase the levitation efficiency, at the expense of the achievable levitation force per unit area.

With the above definition for K , the transition velocity, τ_L (m/sec) is defined as that velocity where $Kv = 1.0$. In practical cases this velocity can be quite low. For example, when $K = 1.0$, $\tau_L = 1$ m/sec or 3.6 km/hr — a slow walking speed. From Equation (3) we then see that when the speed has risen to twice the transition speed, the levitating force has already reached 80 percent of its asymptotic value. Inductrack systems do not require reaching high speeds before lifting off their auxiliary wheels.

From the theory, the magnet weight required to levitate a given pay load can be determined and optimized for a given situation. The parameters that can be used to find the optimal case are the thickness of the Halbach array, d (m), and the wavelength, λ (m). Using Halbach’s theory of his arrays, the dependence of B_0 on magnet thickness

can be evaluated and the optimum thickness determined. Then, given the desired levitation height, the wavelength can be optimized to yield the final answer. For the flat track example given by Equation (7), the result is given by the expression

$$\left[\frac{\text{Weight levitated}}{\text{Weight of magnets}} \right]_{\max(kd, \lambda)} = \frac{0.77 B_r^2}{y_1} = \frac{1.53}{y_1} \quad (9)$$

Here B_r (Tesla) is the remanent field of the permanent magnet. For this optimized case the number of magnet segments per wavelength, M , in the Halbach array has been chosen to be 8, and B_r has been taken to be 1.4T. (high-field commercial-grade NdFeB). If we take, for example, $y_1 = 0.03$ m we find:

$$\left[\frac{\text{Weight levitated}}{\text{Weight of magnets}} \right]_{\max(kd, \lambda)} = 51 \quad (10)$$

If window-frame type track circuits are used, or if inductive loading is employed, or if lower field magnets are used, this ratio will be diminished, with the trade-offs being determined by economic factors.

3. Drive Systems for the Inductrack

There are a variety of drive mechanisms that might be employed in an Inductrack system. A simple one, one that is being implemented in the NASA-sponsored model under construction, is to interleave special drive coils with the levitation coils and then to pulse them in synchronism with the position of the vertical component of the Halbach fields. Second, one could use the linear-induction-motor drive system now being employed in other maglev systems. Third, when the situation permitted it, a shrouded turbo-fan could be employed at the rear of the car to provide drive in open-country areas, while electrical drive-coils embedded in the track could be employed in city areas, with the turbo-fan turned off. Which of these several alternative drives should be used will be determined by economic factors.

4. Stability and Ride-Control Issues

While the use of repelling forces associated with induced currents avoids the stability issues associated with Earnshaw’s theorem, there are other stability-related issues that must be addressed. For example, our theoretical analysis shows that at low speeds, namely near the transition speed, there will exist a slow-growing, parametric-type instability at the natural oscillation frequency of the levitated car. From the theory the natural oscillation frequency of an Inductrack is found to de-

pend only on the wavelength of the Halbach array, being given by the equation:

$$\Omega_0 = \sqrt{2kg} \text{ radians/sec (11)}$$

For typical values of the wavelength the predicted oscillation frequency is of order 2 Hz. The growth-rate of the instability is at its maximum still small compared to this frequency, and it decreases inversely with the square of the velocity, becoming negligibly small at running speeds. Thus the presence of the auxiliary wheels will be expected to suppress the instability at low speeds, and its effect at higher speeds should be negligible, even in the absence of damping. However, issues of passenger comfort will probably demand that some form of oscillation damping be used in Inductrack train applications. We discern several ways in which this damping could be accomplished. The first is to incorporate inertially activated viscous dampers on the train car. A second method would be to employ servo-controlled modulation of auxiliary levitating fields to provide damping forces that are a few percent of the main levitating force. A third method would be to modulate the phase of the drive coils in the track so as to couple with the horizontal component of the Halbach fields, thereby providing controlled incremental vertical forces in such a way as to suppress oscillations.

5. The Inductrack Model

No full-scale demonstration of the Inductrack has been made, so that many practical issues that will have to be faced in such a system have only been addressed theoretically or conceptually. However, there has been constructed and operated a small-scale Inductrack model that confirmed, quantitatively, the predictions of the theory, including stable levitation for speeds above the transition speed.

The model track that was built was 20 meters in length, the first 4.5 meters of which was fitted with drive coils to accelerate and launch a 20 kilogram cart. The launch speed, about 6 times the transition speed of 2 meters/second, was 12 meters/second, corresponding to an average acceleration of about 1.1 g. Following launch, the cart entered the levitating coil section of the track, levitated, and coasted to a stop on its auxiliary wheels at about the end of the track. Except for launching transients, which damped out in flight, the cart behaved stably throughout its flight. Its trajectory was plotted by video imaging, on a screen at the end of the track, the spots from two laser pointers mounted, slightly "cross-eyed," on the cart itself. The cart carried 6 Halbach arrays, two large ones (15 cm wide and 2 wavelengths, i.e. 20 cm in length) on the front and rear of the cart. Below these on each side were two small Halbach arrays that were 2.5 cm high. These side-mounted Halbach arrays

provided sideways stability by interacting with the side legs of the rectangular levitation coils. Each of the levitating coils was rectangular, 15 cm. wide, and 8 cm deep on the sides. Each was wound with 53 turns of 2 mm diameter litz wire. Inductive loading was provided by a line of ferrite "tiles" mounted above and below the lower leg of the coils. The launch section was powered by a series of pulser circuits employing thyristor switched pairs of 1800 mfd, 400 volt electrolytic condensers producing 400-ampere half-sine-wave pulses of duration about 3 to 5 ms, depending on position down the accelerating section of the track. The thyristors were triggered by a series of microswitches mounted alongside the track. These were activated sequentially by a side-mounted "paddle" located on the cart.

6. Future Developments and Summary

Following successful operation of the first model, which was developed under internal Laboratory funding, NASA has undertaken to sponsor the design and construction of a new, higher speed model. NASA's motivation for the work is to investigate the feasibility of launching large rockets by accelerating them up a sloping maglev track to speeds of order Mach 0.8 before firing the rockets. In this way they project saving up to 40 percent of the rocket fuel, opening up the possibility of single-stage-to-orbit missions, with attendant major savings in launching costs. The NASA model now under construction at the Laboratory is designed to electromagnetically accelerate (at 10-g levels) a levitated 10 kg cart up to speeds of order Mach 0.4, over a track that will eventually be about 100 meters in length. Since aerodynamic forces will be substantial, the design of the cart includes provision for stabilization against either upwardly or downwardly directed forces, as well as sideways forces. The project's aim is to demonstrate stable acceleration at high-g levels up to speeds approaching those needed for the final application.

In addition to its potential value to NASA, the new Inductrack model will represent a next step in the direction of the application of the idea to high-speed trains, or, possibly, to lower speed applications where the simplicity of the concept may provide an entry.

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