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January 13, 2004

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A Laminated Track for the Inductrack System: Theory and Experiment

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Abstract: A laminated structure, composed of stacks of thin conducting sheets, has several advantages over a litz-wire ladder as the "track" wherein levitating currents are induced by a permanent magnet array on a moving vehicle. Modeling and experimental results for the laminated track are described and evaluated in this paper. **(Topic #2.1)**

The Inductrack [1] maglev system, being developed for urban maglev applications by a team headed by General Atomics (GA) [2], is under the sponsorship of the U S Federal Transit Administration. An important issue in the development is the "track" within the conductors of which the levitating currents are induced by the permanent magnet arrays (Halbach arrays [3]) on the moving vehicle. GA is using the Inductrack II [4] dual-Halbach-array configuration, in which the track is cantilevered between upper and lower Halbach arrays. The full-scale test track being constructed at GA employs a ladder-like track configuration composed of litz-wire cables encapsulated in stainless-steel tubes of square cross-section.. However, for the future it is important to explore alternative track designs, aiming at optimizing track performance and lowering cost. The laminated track offers opportunities in both of these areas.

The laminated track, described previously [4], involves the use of stacks of thin laterally slotted copper or aluminum sheets, bonded together and reinforced so as produce rigid plate-like structures. The slotting pattern is such as to leave conducting bands at each edge of the sheets. Electrically, the track is thus comprised of a large number of thin, narrow, conductors oriented at right angles to the direction of motion of the vehicle and shorted at their ends, so as to form a pattern of closed circuits. Slotting and stacking the conducting sheets of the track accomplishes several results: First, it forces the induced currents to flow transversely to the direction of motion of the vehicle, thereby optimizing the lifting force of the magnets. Second, by using thin sheets, and by making the conducting strips narrow (typically a millimeter or so) losses due to parasitic eddy currents are minimized, thereby performing a similar function to that accomplished by the use of litz wire in the ladder track. Third, by making the slots narrow, and by bonding the sheets together with insulating adhesive of minimal thickness, the "packing fraction" of the track can be made substantially greater than that of the litz-wire ladder track. High conductor packing fraction and low parasitic eddy current losses imply low drag losses. Other possible economic gains (relative to the litz-wire ladder track) could come from the cost of fabrication, since the cabling, encapsulating, and soldering operations needed to fabricate the litz track are not required in the laminated track.

The LLNL theory extends a previous approximate "lumped circuit" analysis of the Inductrack [1]. In this analysis the track is looked on as a coupled assembly of conducting loops, the area, inductance, and resistance of which are employed to calculate the currents induced by the moving Halbach arrays, and from these currents then to deduce lift and drag forces. The component of the inductive coupling of the circuit array associated with inter-layer mutual inductance is ignored. Using this approximation, an "equivalent conductor" is defined based on the width of the laminated track conductors and the total thickness of the sheet stack. The current and the lift and drag forces on this equivalent conductor are calculated as the resultant of the sum of the surface currents and the parasitic eddy-currents that would have been calculated for thin conductors at vertical locations within the track, using the surface-current-calculated inductance where needed. In the limit of slots wide compared to the width of the Halbach arrays the

"equivalent conductor' approximation should be a good one, and in the case where the levitation gap is small compared to the width of the Halbach arrays, the 2-D fields should represent a reasonable approximation to the actual 3-D fields. As it turned out, and as verified by the work at Carnegie Mellon, the above approximations proved to be useful ones for design purposes, with the 3-D calculations always being available to insure that excessive errors are not being made.

The LLNL laminated track test rig was designed to provide a means for benchmarking the CMU and LLNL codes, using scaled-down versions of the Halbach arrays used in the GA full-scale system. To insure that inertial effects play no role in the measurements the test rig employs a moving track, guided on precision rails and propelled by a pulley-and-weight drive system. The dual Halbach arrays are mounted on a rigid frame with two degrees of freedom, also equipped with precision guide rails. Force sensors are used to determine the lift and drag forces while the track moves through this assembly, with track velocity being simultaneously measured by a tachometer generator. In the tests two different Halbach array configurations were tested. The first tested was a "5-block-wide" Inductrack I (single Halbach array) configuration, followed by a "5 x 3 block-wide" Inductrack II configuration. The reason for first using the single Halbach array configuration is that in this configuration the Lift/Drag ratio is independent of errors in measuring the levitation gap. Together with the resistance of the circuits (which can be calculated), it provides a way to check the theoretical value of the inductance, L. In this measurement, and also in the "5 x 3" measurements, good agreement was found between the LLNL code and the experimental results, using the theoretical L value. Fig. 1 presents plots of the lift and drag forces as a function of track velocity for the Inductrack I setup. Shown are theoretical curves, the central one of which is for the gap as measured in setting up the experiment. The two other curves are for gaps that are 1 mm. greater and 1 mm. less than the measured gap. Shown superposed are the experimental data points.
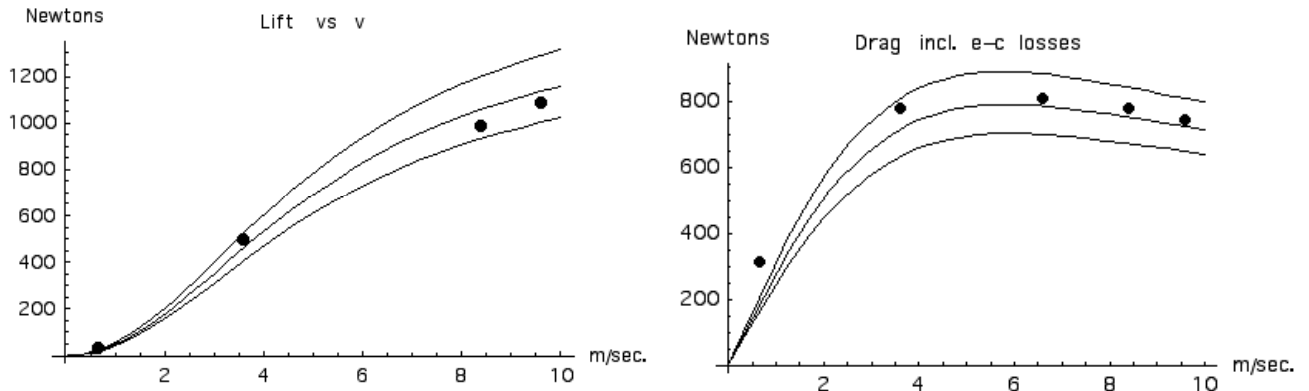

Fig. 1. Comparisons of Lift and drag forces from LLNL 2-D code and Inductrack I test rig results.

An alternative "field based" modeling methodology developed at Carnegie Mellon University (CMU) accounts for the full three-dimensional structure of the magnetic field that is imposed by the Halbach array permanent magnets and describes the self-consistent mutual coupling between two-dimensional induced currents in the individual layers of the laminated track.

The three-dimensional structure of magnetic fields due to the Halbach array permanent magnets is computed in the CMU model by superimposing contributions from patches of magnetization surface charge density at each magnet face where the magnetization is discontinuous [5]. By retaining only the first Fourier component of the fields in the direction (y) of travel, as shown in

Fig. 2 for one full wavelenth of a 5 X 3 double Halbach array, a description is obtained that accurately accounts for the three-dimensional structure of the source fields in the width-wise (x) direction, and that can be used in a two-dimensional description of the resulting induced currents.
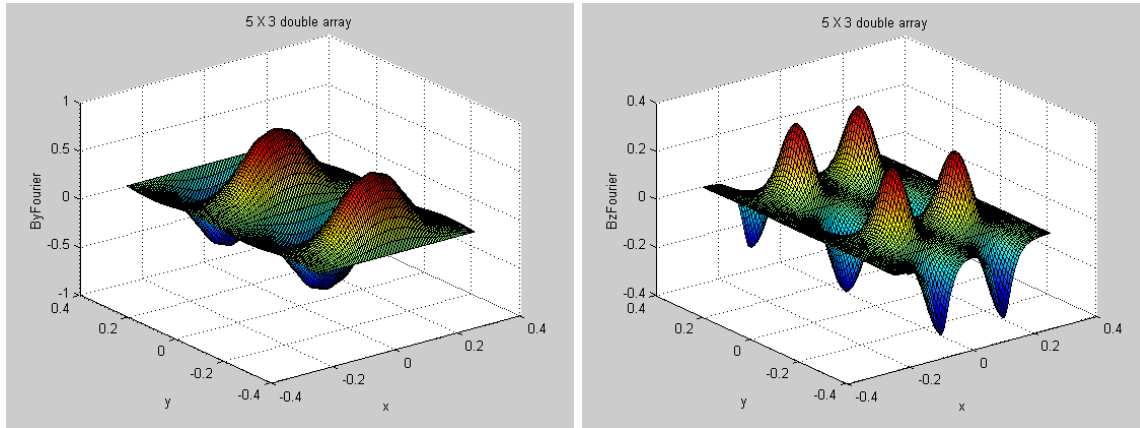

Fig. 2. First Fourier components of longitudinal (y) and vertical (z) components of magnetic flux density over a plane at the center of one lamination for Inductrack II configuration.

In the description of induced lamination currents, the total fields at each layer height are a superposition of the source fields, the fields due to induced currents in all other layers, and the fields due to induced currents in the layer itself. Thus, the inter-layer mutual inductance is fully accounted for. The resulting lift and drag curves are qualitatively and quantitatively similar to those obtained from the LLNL lumped circuit theory. The Lift and Drag values in Table I illustrate the agreement between the CMU and LLNL codes and the LLNL test rig results (velocity of 8 m/sec. for the cases tabulated.) for the 5 X 3 Inductrack II configuration.

	CMU code	LLNL code	Measured
Lift	680 N	680 N	800 N
Drag	220 N	220 N	220 N

Table I. Calculated and measured values of lift and drag at 8 m/s, 5 X 3 Inductrack II test rig.

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