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# DEVELOPMENTS IN UNDERSTANDING STABILITY AS APPLIED TO MAGNETIC LEVITATED LAUNCH ASSIST

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## ABSTRACT

Magnetic levitation is a promising technology, with the potential of constituting the first stage of a third generation space transportation system. Today, the Space Shuttle burns on the order of one million pounds of solid rocket propellant to bring the orbiter and external tank to nearly Mach 1 (1,000 kph). Imagine the reductions in launch vehicle weight, complexity and risk if an aerospace vehicle could be accelerated to the same speed utilizing about $1,000 of off-board electrical energy stored in flywheels. After over two decades of development, maglev trains travel on full-scale demonstration tracks in Germany and Japan reaching speeds approaching 500 kph. Encouraging as this may appear, the energy and power required to accelerate a 1 million pound launch vehicle to 1,000 kph would radically redefine the state-of-the-art in electrical energy storage and delivery. Reaching such a goal will require levitation with sufficient stability to withstand an operating environment fundamentally different from that of a high-speed train. Recently NASA let contracts for the construction of three maglev demonstration tracks. This construction and several associated trade studies represent a first-order investigation into the feasibility of maglev launch assist. This report provides a review of these efforts, other government sponsored maglev projects and additional technical literature pertinent to maglev stability. This review brings to light details and dimensions of the maglev stability problem which are not found in previous NASA-sponsored trade studies and which must be addressed in order to realize magnetic levitation as a launch assist technology.

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## 1. Historical Overview

First, Table 1 presents a very brief history of maglev developments. Then more recent events sponsored by the National Aeronautics and Space Administration (NASA), the Federal Department of Transportation (DOT) and the Department of Defense (DOD) will be briefly reviewed. Afterward, the focus will shift to the topic of levitation stability. It is the author's belief that this topic represents an unresolved, potential obstacle to realizing maglev as a space launch technology. Finally, this report will pose additional questions and suggest future paths NASA research and development.

- 1842 Earnshaw publishes theorem showing stable levitation of a magnet is impossible in a static magnetic field [1]
- 1910 – 1914 French émigré to Britain, Emile Bachelet, an electrician, builds and patents first prototype maglev vehicle the size of a toy train.
- 1956 Early paper on aspects of levitation, Philips Research Reports [2]
- 1966 Powell and Danby receive patent for null-flux coils for maglev
- 1972 Seminal work by researchers at Ford on electrodynamic lift and drag [3]
- 1970-75 M.I.T. Magnaplane project underway, funded by federal DOT.
- 1977 Eric Laithwaite's book on linear motors [4]
- 1991-94 National Maglev Initiative (NMI) underway
- 1997 articles on null-flux coils [5] and Rote's NASA Langley report [6].
- 1999 Thompson's dissertation on high $T_c$ superconducting maglev
- 2002 Rote publishes review article on electrodynamic stability

To gain a historical perspective, the reader is referred to [4], [7] and, if one is pressed for time, [10]. Also useful is the final report of the National Maglev Initiative. A listing of websites, which index other maglev links, are found in this project's deliverables. Rather than cite individual sources for technical information, the reader is directed to the bibliographies found in [8] and [10].

NASA's interest in maglev dates from the Highly Reusable Space Transportation (HRST) concept studies conducted in the early 1990's. These studies paralleled renewed interest in American R&D sponsored by the DOT's NMI. In the late 1990's, NASA's Marshall Spaceflight Center (MSFC) let contracts for the design and construction of three maglev demonstration tracks. A separate contract was let to the Center for Electro-mechanics (CEM) at the University of Texas at Austin. CEM's report represents a thoughtful "order of magnitude" analysis of the feasibility of electromagnetic launch assist. CEM paid special attention to scaling laws and then applied them to estimate the requisite electric motor and flywheel technology.

The DOT's interest in maglev derives from the Inter-modal Surface Transportation and Efficiency Act of 1991 (ISTEA) and in 1998, the Transportation Equity Act for the 21st Century (TEA-21). The ISTEA funded the NMI and one deliverable from the NMI will be reviewed later in this report. TEA-21's impact on space launch assist has been indirect: active government funding helps to sustain maglev interest in certain R&D-oriented industry partners. As to ground transportation, TEA-21 may begin construction of a commercial maglev rail line in the Northeast prior to its termination in 2006. Since American maglev technology was not developed during the late 1970's and 1980's, the DOT expects to purchase Germany's *Transrapid* technology. *Transrapid* is Thyssen-Krupp's brand name for their electromagnetically levitated, actively controlled maglev train. Siemens, a German company better known to the American public, is a division of Thyssen-Krupp.

During the mid and late 1990's a 100-ft.-long maglev modification was made to the Holloman Air Force Base High Speed Test Track (HSTT). Since the 1950's the HSTT has been the premier facility for testing ejection seats, near-ground hypersonics and the human limits to high-speed acceleration and jerk (the time rate of change of acceleration). Holloman's maglev modification relied on superconducting magnets, which suffered from repeated quenches (the magnetic equivalent of a melt-down). The industry partners (General Atomics, Boeing, Bechtel and Foster-Miller) redesigned the sled as funding expired. However, additional funds were not appropriated to build a redesigned sled.

The Navy's Electromagnetic Launch System (EMALS) is currently in its second phase of development. To date, the Navy has let two contracts each worth $60M to two competing industry teams (one lead by General Atomics and the other by Northrup-Grumman). An EMALS would not employ magnetic levitation but it must design a linear motor capable of accelerating a 100,000 lb. Aircraft to a speed of 67 m/sec (130 knots) on a short (330 ft.) aircraft carrier runway. This represents a vehicle 10% of the weight and 22% the proposed launch speed of a maglev first stage. The Navy's EMALS program will face similar challenges to store and deliver sufficient electrical energy to a linear motor just as an operational maglev train or launch assist system would. [11] The two EMALS teams are contracted to deliver a design study and scalable demonstration hardware by 2003. Installing an EMALS on an aircraft carrier must wait Congressional funding of a Next Generation Carrier. This is not expected until after 2006. Later in this report attention will return to these two DOD projects.

## 2. Recent NASA Development

The salient features of the three NASA demonstration tracks are summarized in Table 2. Note that EDL refers to ElectroDynamic Levitation and is often described as either 'repulsive' or 'passive' levitation, due to magnetic induction via Faraday's and Lenz's Laws. EML refers to ElectroMagnetic Levitation and relies on active feedback control of the "attractive" forces between electromagnets and ferrous metal rails. Accompanying the Foster-Miller Track was another "order of magnitude" analysis of the power requirements and scaling for electromagnetic launch assist. Both the CEM and Foster-Miller studies reach the conclusion that accelerating a 1 million pound (455,000 kg) vehicle to 0.85 Mach (300 m/sec) would require a track length of about 3 km. Such a 'Maglifter' vehicle program would redefine the state-of-the-art in flywheel energy storage (24 GJ) and pulsed power distribution (approximately 5 GW). Nevertheless, both studies believe this goal is eminently reachable given current technology: approximately 9 steel flywheels of the size used in electric generating plants (most of which would be located at the high-speed end of the track).

| Prime Contractor | Type of Levitation | Disposition | Notable Features |
|---|---|---|---|
| Foster-Miller Inc. | EDL using permanent magnets and null-flux coils | Delivered to KSC, relocated to F.I.T. | Being outfitted with sensors. |
| Lawrence Livermore National Laboratory (LLNL) | EDL using Halbach arrays of permanent magnets and null-flux coils | Currenttly at LLNL | Communicated incorrect null-flux coil perimeter to manufacturer. Excessive magnetic drag. |
| PRT Advanced Maglev Inc. | EML using powered coils separate from propulsion | Located at MSFC | Flywheel delivers power to propulsion coils. |

**Table 2. Description of the Three NASA-sponsored Maglev Demonstration Tracks**

These studies [11], [12] constitute only a first step, in terms of system design, sub-system scaling and modeling sophistication. For example, in both reports, aerodynamic drag is modeled by assuming a drag force of $F_d$ = □□$C_d v^2$. Here, □ is the mass density of air, A is a frontal cross-section area of a levitated vehicle, $v$ is the vehicle's speed and the drag coefficient ($C_d$) is written as a function proportional to the square of velocity. As such, the power loss to aerodynamic drag is approximately equal to that required to overcome the payload's inertia. Power and energy requirements are obtained strictly from the equations of one-dimensional kinematics. Power loss from induced drag (also known as vortex shedding from an airfoil) is not included in either report. This would certainly be a contributor since all current second generation space shuttle concepts include one or more lifting bodies stacked piggy-back style or end-to-end. Aeroelasticity considerations are also beyond the scope of these 'first-pass' estimations. Also, the above expression for drag force does not take into account drag arising from the concrete guideway, in which the maglev carrier must ride. Both reports account for magnetic drag (also known as eddy-current drag) with lift and drag expressions equivalent to those derived in [3]. However, both reports do not contain a list of references to indicate the extent of the literature search performed as part of the studies.

## 3. Analytical Background of Magnetic Lift and Drag

Equations (1) and (2) are plotted in Figure 1. The inset drawing depicts the physical situation: a wire carries current, ($I_0$) into the plane of the page and moves with constant speed $V_0$ in the positive x direction over a conducting sheet of thickness □ and conductivity □. Note that $w = 2 / (\mu_0 \sigma \Delta)$ is a characteristic speed.

$$F_{lift} = \frac{\mu_0 L I^2}{4\pi h} \frac{V_0^2}{w^2 + V_0^2} \qquad (1)$$

$$F_{drag} = \frac{w}{V_0} F_{lift} \qquad (2)$$

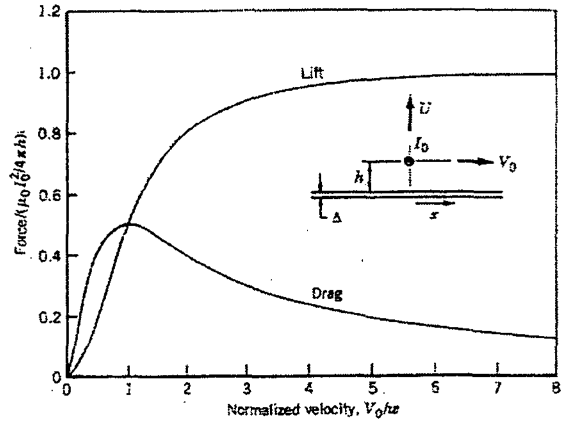


**Figure 1. Lift and Drag as a Function of Speed (Moon 1994)**

These equations arise by first combining Faraday's, Ohm's and Ampere's Laws, to show that $A$, the magnetic vector potential, must satisfy Eqn. (3). $A'$ is the vector

$$\frac{\partial(\bar{A}' + \bar{A})}{\partial t} = w\frac{\partial \bar{A}}{\partial z} \qquad (3)$$

potential due to the source current and $A$ is the vector potential due to the eddy currents. This is accomplished if $A'$ is independent of time and $A(x,y,z,t) = -f_1(x,y,z+z_0+wt) + f_2(x,y,z+z_0+wt)$. This allows a representation where the moving source current generates a 'trailing wake' of repeated image currents below the conductive sheet. The first image current is the same distance below the sheet as the source is above it. However additional images trail behind the first image and move down in the negative z direction at the *same* characteristic speed $w$ as mentioned previously. Applying this representation, allows simpler, familiar expressions for the magnetic fields due to poles, dipoles and current loops to be modified by assuming equivalent image currents and then computing a magnetic field. The Lorentz Force Law ($\boldsymbol{F} = \boldsymbol{Il} \times \boldsymbol{B}$) then determines the forces on the source. Both lift and drag components arise from the vector cross product.

## 4. Analytical Background of Negative Damping

As mentioned above, both the CEM and Foster Miller studies accounted for magnetic drag. However, as early as 1974 [13] negative damping was recognized as a characteristic of EDL. Iwamoto considered negative damping in the context of a superconducting magnet and later in 1984, Moon showed this type of positive feedback was a general consequence of the eddy current distribution. Moon summarizes this paper in his 1994 book and states that a sinusoidal perturbation in the height of a current element moving over a conducting sheet results in negative damping.

Suppose the height of the current oscillates slightly. After performing a linear perturbation analysis of the resulting change in magnetic field, a perturbing lift force $F'_{lift}$ is obtained. The first term in Eqn. (4) represents a spring-like restoring force however □ is velocity dependent. If the speed $v$ is larger that the characteristic speed $w$, then the □ changes sign and negative damping results.

$$F'_{lift} = -\kappa \frac{z}{h_0} - \gamma \frac{dz}{dt} \quad (4)$$

$$\gamma = \frac{\mu_0 I^2 w}{4\pi h_0} \left( \frac{w^2 - v^2}{\left(w^2 + v^2\right)^2} \right) \quad (5)$$

This type of magnetic negative damping is of the same type of oscillatory instability as aeroelastic *flutter*. Flutter is technically distinct from resonance, which derives from an external, time dependent forcing function. Perhaps the best-known example of aeroelastic flutter is the Tacoma Narrows bridge collapse of 1940. This event is often characterized as resonance associated with a (Von Karmann) wake of vortices shed from the bridge span. However, further analysis showed the bridge collapsed due to a self-exciting, motion-induced train of vortices at a different frequency. This self-excitation is the fundamental difference between negative damping and traditional resonance in an undamped or under-damped oscillator. [14]

## 5. Time Dependence of Forces Due to Null-flux coils

The Foster-Miller maglev track and the Holloman HSTT upgrade used null-flux coils in the sidewalls of the guideway. A null-flux coil is a tight, closed-loop, figure eight winding of insulated wire. The sled's (or bogie's) magnets usually have a pole surface area as large (or larger) than the null-flux coil. When one of these magnets passes by the coil, it will induce a voltage (and hence a current flows) in the coil. If a current flows clockwise in the upper half of a closed figure eight loop of wire, the same current will necessarily flow counter-clockwise in the bottom half of the figure eight. If the bogie's magnet moves past a null-flux coil above the center of the coil (where the wires in the coil cross) more magnetic flux will link with the upper half of the coil and induce a larger current. Lenz's law dictates that the coil's induced current (and it's induced magnetic field) will oppose that of the bogie's magnet, thereby forcing the bogie down toward the center of the figure eight. The center of the coil is the null-flux position since this is where the magnet's motion induces zero net flux in the complete figure eight.

Null-flux coils are usually mounted vertically in the sidewalls of guideway. This has the added advantage of moving the levitation out from under the bogie, which opens that space for the linear motor. Also, adjacent (but separate) pairs of coils with rectangular windings can also be used in place of figure eight coils. To distinguish, this arrangement is called a flux-eliminating coil.

To summarize, null-flux coils have two advantages over a guideway made from a continuous sheet of aluminum or copper. First, null flux coils provide a built-in restoring (stabilizing) force. Powerful motivation when one recalls Earnshaw's theorem. Second, null flux coils provide significantly less drag than a continuous sheet guideway. However, it is equivalently true that null-flux coils provide only a minute amount of damping. The self and mutual inductance and the wire resistance are all very small. Hence, this stability only exists in an ideal, unperturbed scenario.

Moreover, the restoring force provided by a flux-eliminating coil has "spiky" time dependence. Thus, even when a maglev bogie moves past a long line of null-flux coils at a constant speed, an off-center magnet will experience a series of discrete, restoring impulses shaped (in time) much like a triangle wave [5]. Triangle waves have a Fourier representation of odd numbered frequency multiples: $A_1\sin(\Box t) - A_2\sin(3\Box t) + A_3\sin(5\Box t) \ldots$ This yields a spectrum, which peaks at a low fundamental frequency and has progressively smaller higher frequency components.

Of course, the nominal operating mode for the launch of a space vehicle is acceleration not constant velocity (as in a maglev train). The net qualitative effect will be to re-shape the triangle waves and make them spikier. Simultaneously, the bogie will encounter an accelerated (compressed in time) sequence of these re-shaped restoring forces. This compression will distribute mechanical energy to higher frequency components. This has the potential of making available multiple resonant frequencies, which may be excited by various perturbations.

## 6. Efforts to Improve Magnetic Damping

The Holloman upgrade employed superconducting magnets wound from NbTi wire (cable in copper conduit construction was not used). Also, no method was used (pressurizing or on-board refrigeration) to reclaim the helium that boiled out of the cryostat. Loss of liquid helium was reported as no more than 30%. A year 2000 AIAA report on the Holloman effort listed the conclusion of a General Atomics investigation into the cause of the quenches. Apparently, impulses deriving from the null-flux coils (as mentioned previously) and impulses from the rocket engines imparted vibrations (at 2 KHz) to a magnetic damping plate built on the sled over the superconducting magnets. The heat from the vibrations warmed the magnets and triggered the quenches.

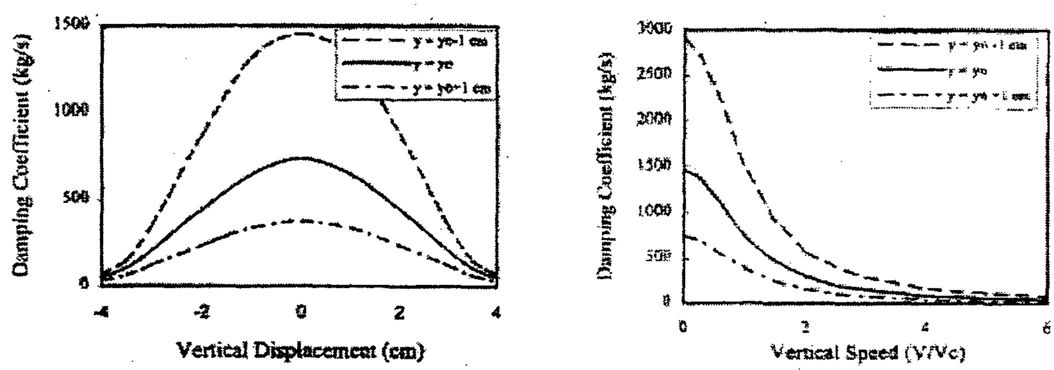


**Figure 3. Damping decreases with vertical displacement (left) and vertical speed (right)**

Holloman was conducting its tests in late 1997 and early 1998. At that time, two researchers at Argonne National Laboratory were on contract to Holloman AFB. They published a short paper [14] examining the magnetic characteristics of the damping plate. Their analysis is summarized in Figure 3. Here they calculate the damping coefficient as a function of vertical displacement from the null-flux position (zero on the horizontal axis). Ideally, one would prefer to see damping *increase* as the bogie moves away from equilibrium rather than decrease as a function of vertical displacement or vertical speed.

| Moving along | Descriptor | | Rotating about | Descriptor |
|---|---|---|---|---|
| X – axis | Forward | | X – axis | Roll |
| Y – axis | Lateral or sway | | Y – axis | Pitch |
| Z – axis | Vertical or heave | | Z – axis | Sway |

**Table 3. Definitions of Terms Used in Maglev Vehicle Dynamics**

## 7. Further Complications: Coupled Modes and Nonlinear Forces

Yet another challenge to designing a stable, EDL maglev system, which delivers good 'ride quality', is that the modes of oscillation of a generic maglev vehicle couple between differing degrees of freedom (DOF). Recall that for rigid bodies an object may move in six DOF's: translation along *and* rotation about the x, y and z axes. In general, analyzing the dynamics of a maglev vehicle involves solving Lagrange's equation and using magnetic circuit analysis as the input. An array of self and mutual inductance calculations must be a part of the circuit analysis. Reference [10] summarizes this approach and then focuses attention on a simplified vehicle constrained to just three degrees of freedom (±x, ±y, and rotations about the z axis). He shows (both analytically and with some experimental data) that such a vehicle is capable of coupled lateral-yaw oscillations that exhibit flutter. Table 3 defines common terminology. Coupling along four modes is possible as described in Table 4.

| Coupling | Descriptor | Type of Instability |
|---|---|---|
| Lateral-roll | Listing to one side | Divergent (static) |
| Pitch-heave | Porpoising | Oscillatory |
| Lateral-yaw | Snaking | Oscillatory |
| Yaw-roll-pitch | Screw motion | Oscillatory |

**Table 4: Coupled Modes of Instability**

Two other, non-coupled, modes of instability are possible: an oscillatory 'hunting' forward and backward along the x – axis and vertical or 'heave' oscillations along the z – axis. With sufficient x-acceleration and minimal motor slip, hunting may not be an issue for space launch assist. Vertical oscillations, however, must be damped out. Since magnetic forces are intrinsically non-linear, vertical perturbations can cause a departure from simple harmonic motion and generate chaotic oscillations [10]. One potential source of perturbations is flexure of the guideway due to theg weight of the vehicle. The oscillations may enter a limit cycle (an orbit in phase-space that does not close on itself). Collaboration between researchers at NASA-Langley and NASA-Ames has developed a Non-linear Generalized Predictive Control (NGPC) algorithm to actively control EML of an iron ball floating beneath an electromagnet. [16]. Though magnetic forces are intrinsically non-linear, the vast majority of stability studies employ linear approximations in EDL and linear control theory in EML. Simulated neural network may be especially well suited to EML.

## 8. Summary and Future Directions

The challenges of designing a stable maglev system based on electrodynamic repulsion using null-flux coils involves overcoming (i) near zero intrinsic damping, (ii) negative damping terms arising from eddy/image currents, (iii) spiky restoring forces, (iv) compression of restoring impulses when accelerating, (v) the effectiveness of passive damping plates/coils decreasing as a function of distance from the null-flux position, (vi) coupling of instability modes, (vii) the potential for chaotic dynamics.

Japan Railway (JR) has over twenty years of development experience in using superconducting magnets in EDL systems. Until recently, JR has exclusively relied upon passive damping from the generation of eddy currents in the cryostats, which house the superconducting electromagnet. More recently, JR has used modulated control of the power to the linear motor to reduce instabilities [17]. In a recent paper [9], Rote and Cai, review the history of individual and coupled modes of instability. The authors conclude with a call for those developing full-size maglev trains to fully address whether these instabilities exist or how they have been surmounted.

A group at M.I.T. proposed another avenue to maglev stability as part of the National Maglev Initiative. In their study and computational model, aerodynamic control and a secondary, passive suspension system provided adequate system stability: on the order of ±2 cm of primary suspension displacement when control of vertical and lateral flaps on the winglets were assumed.

Also General Atomics of San Diego has constructed a six DOF dynamical, computer model to assess their wheel-based, limited DOF test apparatus. This model includes a passive secondary suspension and seems to be adequate to suppress instabilities [18]. However, General Atomics' urban maglev project is a low-speed application of maglev when compared to a 1,000 Km/hr. Maglifter concept.

Clearly, there is a constellation of challenges to stabilizing an EDL system. Options for further research and development include:

- Use superconducting magnets. They add complexity, but offer a mechanism for damping as well as larger and safer (7 to 10 cm) vehicle guideway gaps.
- Perform modeling on designs of null-flux coils, which include iron. This would remove stored energy in the coils, which is an impediment to damping.
- Investigate novel methods of damping in null-flux coils such as active magnetic damping with control coils between vehicle magnets and guideway coils.
- Perform a critical review of existing six DOF dynamical models to assess the efficacy of passive secondary suspensions in the environment of launch assist.
- Motivate developers of simulation software to integrate aerodynamics, aeroelasticity into their products.
- Investigate the use of high critical temperature superconductors, which tolerate A/C eddy current effects that were at the root of Holloman's quenching.

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