Prediction of Lift and Drag Forces in an EDS Maglev System

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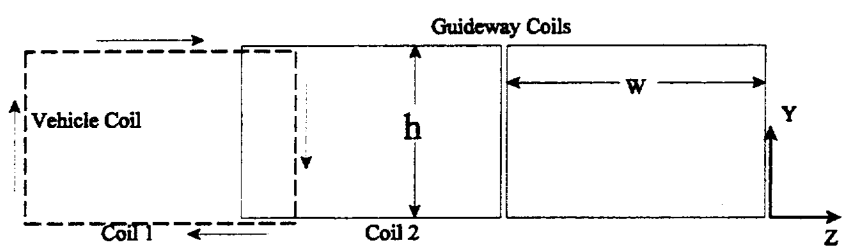
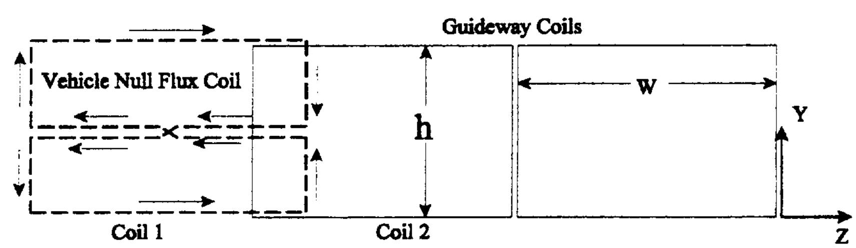
Abstract

This document examines the tradeoffs of choosing a null flux excitation system versus a simple coil excitation. In both cases the guideway is considered to be a simple "O" shaped coil positioned vertically on the track. An analysis of both shows that the null flux excitation provides equivalent lift to the open coil system with less drag; further the lift is stabilizing in both directions for the null flux excitation. The full rectangular excitation coil proves to be excellent for guidance especially if the vehicle magnets/coils on either side are arranged in repulsion. The rectangular coils in attraction prove to be expensive for drag production and unable to produce downward restoring forces.

Introduction



(a) Rectangular shaped excitation coil translating past "O" shaped guideway coils.

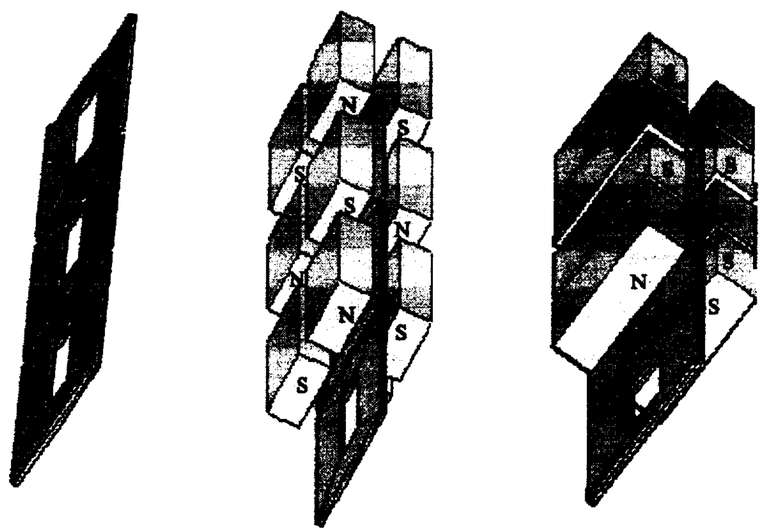


(b) Null flux excitation vehicle coil weeping past fixed guideway coils.

Figure 1 Rectangular (a) and null flux (b) vehicle coils sweeping past fixed guideway coils.

The innovation of null flux coils in Maglev systems goes back to 1966 when Danby and Powell suggested their use in the first EDS system with superconducting magnet coils [1][2]. The dynamic stability of such systems have been studied experimentally and through mutual inductance approaches by Rote [3][4]. The mutual inductance coupling approach for the prediction of forces in such systems is adopted in this study. EDS systems that do not use flux canceling techniques have also been proposed and tested (e.g. Magneplane [5]), but these systems have a much poorer lift to drag ratio. Perhaps the best review of the state of the art for this type of system is found through the Japanese Rail program in Japan where these techniques have demonstrated 550 kph operation in the Japanese rail test prototype [6].

The goal of this paper is to compare the null flux excitation to a full O coil excitation and then predict the lift and drag generally for a null flux excitation. Figure 2 shows the two options being compared along with the guideway coils. The full rectangular coils in inset (c) experience a repulsive force away from the guideway coils with any displacement. One way to make such a system stable is to place a second set of guideway coils vertically over the first set. The full rectangular system coils will experience a downward force by this second set of coils.



(a) Guideway Coils (b) Null Flux Excitation (c) Rectangular Coil Excitation

Figure 2 Null flux and rectangular excitation of O shaped guideway coils.

Geometry

Designers seek advantages for different coil configurations; Comparative assessment of coil configurations can only be obtained quantitatively. An electrodynamic O shaped coil guideway system is considered in this paper. A simple cost effective guideway structure consists of "O" shaped conducting coils placed vertically in the guideway as depicted in Figure 1(a). The dotted rectangular excitation coil can be considered a simple coil, a superconducting loop, or a permanent magnet. As it sweeps past the guideway coils, it induces a current which attempts to oppose the flux change. When the coil is offset vertically in the y direction, a force is generated to further push it off center.

This system will be contrasted with the null flux system shown in Figure 1(b). The excitation coil supports oppositely directed flux through the upper and lower portions of the windows of the coil. When the coil is centered vertically, no current is induced in the guideway coils. When the excitation coil is displaced in the y direction, a current is induced which does the opposite of that in Figure 1(a). The induced current from the null flux coil exerts a force on the coil to restore it to its centered position. This is the well known benefit of the null flux geometry and why it has become so popular.

Analysis

To perform a useful comparison of these two systems, it is useful to make some approximations to pertinent quantities. One of the most important quantities is the mutual inductance coupling between the vehicle coil 1 and the fixed guideway coil 2. Let z=0 refer to the position in which the vehicle and guideway coil directly overlap. Let z=0 refer to the position in which the window of the guideway coil matches the vertical position of the window of the vehicle coil. The vehicle coil straddles the guiderail, and is wound in series, so it can be thought of as a single coil. In this embodiment, the mutual coupling of the rectangular coil in Figure 1(a) is

$$M_R = M_0(x)\cos(\frac{\pi}{2h}y)\cos(\frac{\pi}{2w}z) \equiv M_0\cos(\frac{\pi}{2h}y)\cos(kz). \tag{1}$$

The mutual coupling of the null flux coil in Figure 1(b) with the guideway coil is approximately

$$M_N = \frac{M_0(x)}{2}\sin(\frac{\pi}{h}y)\cos(\frac{\pi}{2w}z) \equiv \frac{M_0}{2}\sin(\frac{\pi}{h}y)\cos(kz). \tag{2}$$

The x dependence is omitted from these expressions, but it commonly is a linear function that starts with zero when the coil is centered laterally, and grows linearly as the vehicle coil gets closer to the guideway coil on one side.

Regardless of which system is employed, the current induced in the shorted guideway coil 2 depends on M, the self inductance of the guideway coil L_2, and the resistance of the guideway coil R_2 as

$$L_2\frac{dI_2}{dt} + R_2I_2 + \frac{d}{dt}(MI_1) = 0. \tag{3}$$

The induced current in the low and high frequency limit become

$$I_2 = -\begin{cases} \dfrac{M(y)I_1\cos(kvt)}{L_2}; & low\ frequency \\ \dfrac{M(y)I_1kv\sin(kvt)}{R_2}; & high\ frequency \end{cases}. \tag{4}$$

Equation (4) assumes that the vehicle speed is v, so that z=vt, and M(y) is either the cosine in (1) or the sine in (2). The current I1 is assumed fixed, being the representative current of the superconducting coil or magnet. Equation (4) can be written for any speed by allowing ω=kv, and writing the result in phasor format as

$$I_2 = -\frac{j\omega M(y)I_1}{(j\omega L_2 + R_2)}e^{j\omega t}. \tag{5}$$

Of interest are the forces generated on the vehicle coil as it sweeps past the guideway coils at speed v. These forces are easily derived through the derivative in the various directions of the coenergy

$$W' = MI_1 I_2 \tag{6}$$

holding the respective currents constant during the spatial derivative. The average of the z directed drag force is

$$\hat{F}_z = \frac{1}{2}\,\Re\,(\frac{\partial M}{\partial z} I_1 I_2^*)\,. \tag{7}$$

Inserting (5) and (6) into (7) yields for the rectangular vehicle coil

$$\begin{aligned}\hat{F}_z &= \frac{1}{2}\Re\left\{\frac{jkM_0\cos(\frac{\pi}{2h}y)\left(e^{j\omega t}\right)^* I_1\left(-j\omega M_0\cos(\frac{\pi}{2h}y)I_1 e^{j\omega t}\right)}{(j\omega L + R)}\right\}\\ &= \frac{1}{2}\Re\left\{\frac{k\omega(M_0\cos(\frac{\pi}{2h}y)I_1)^2}{(j\omega L + R)}\right\}.\end{aligned} \tag{8}$$

When the same procedure is performed on the null flux system, the result is

$$\begin{aligned}\hat{F}_z &= \frac{1}{2}\Re\left\{\frac{jk\frac{M_0}{2}\sin(\frac{\pi}{h}y)\left(e^{j\omega t}\right)^* I_1\left(-j\omega\frac{M_0}{2}\sin(\frac{\pi}{h}y)I_1 e^{j\omega t}\right)}{(j\omega L + R)}\right\}\\ &= \frac{1}{8}\Re\left\{\frac{k\omega(M_0\sin(\frac{\pi}{h}y)I_1)^2}{(j\omega L + R)}\right\}.\end{aligned} \tag{9}$$

Of central importance is the ratio of the drag with the rectangular non-null flux system and the null flux system,

$$\frac{\hat{F}_{zR}}{\hat{F}_{zN}} = \frac{\left[M_0\cos(\frac{\pi}{2h}y)\right]^2}{\left[\frac{M_0}{2}\sin(\frac{\pi}{h}y)\right]^2} \approx \begin{cases}\left(\frac{2h}{\pi y}\right)^2 \Big|_{\text{for small } y}\\ 4\,\Big|_{\text{at their maximum positions}}\end{cases}. \tag{10}$$

The drag force is substantially larger than it is with the rectangular non-null flux coil system for small y. As will be shown shortly, the rectangular system reaches a lift force maximum at $y=h/2$, and is stable for $h/2<y<h$. The null flux system reaches a lift force maximum at $y=h/4$, and is stable for $0<y<h/4$. At these respective maximums the rectangular system has four times the drag of the null flux system. This is not the total story since the other component forces should be investigated.

The y component of the rectangular coil system is

$$\hat{F}_y = \frac{1}{2}\Re\left(\frac{\partial M^*}{\partial y} I_1 I_2\right) = \frac{1}{4}\Re\left\{ j\omega (M_0 I_0)^2 \frac{\pi}{h} \frac{\cos(\frac{\pi}{2h}y)\,\sin(\frac{\pi}{2h}y)}{(j\omega L_2 + R_2)} \right\}. \tag{11}$$

Similarly, the average lift force from the null flux system is

$$\hat{F}_y = \frac{1}{2}\Re\left(\frac{\partial M^*}{\partial y} I_1 I_2\right) = -\frac{1}{8}\Re\left\{ j\omega (M_0 I_0)^2 \frac{\pi}{h} \frac{\sin(\frac{\pi}{h}y)\,\cos(\frac{\pi}{h}y)}{(j\omega L_2 + R_2)} \right\}. \tag{12}$$

The null flux system has a sign reversal from the derivative of the cosine rather than the sine; this sign reflects its inherent stability. The rectangular system has to have a different initial positioning for repulsion to work. Stability for the rectangular system is achieved if the rectangular coil is positioned above the maximum lift position $y \geq h/2$. The null flux coil system delivers maximum lift at $y=h/4$; any vertical displacement after that point becomes unstable. The all important ratio of these two lift forces is

$$\frac{\hat{F}_{yR}}{\hat{F}_{yN}} = \frac{2\sin(\frac{\pi}{2h}y)\,\cos(\frac{\pi}{2h}y)}{\sin(\frac{\pi}{h}y)\,\cos(\frac{\pi}{h}y)} \approx \begin{cases} 1 & \textit{for small } y \\ 2 & \textit{at their respective maximum positions} \end{cases}. \tag{13}$$

The two systems can generate the same lift forces in a stable configuration, but the drag for the rectangular system is horrendously bad. The mutual coupling M is low for the null flux system, while the derivative $\frac{\partial M}{\partial y}$ is low for the rectangular system; the two compensate. At their respective maximums, the rectangular system generates twice the lift of the null flux system, and as shown in (10), four times the drag.

The lateral guidance forces are the last to compare. The lateral derivative on the mutual coupling enters prominently in the calculation. Consider the null flux geometry displayed in Figure 3. Stacked magnets are used to simulate a null flux excitation. The "O" shaped guideway coil is shown as comprised of thirteen individual conductors as it must to minimize eddy current losses. Two identical coils are shown side by side. The two pairs can be connected together in series to emulate a single coil, or they can be cross-connected so that their flux cancels. The later embodiment is of little value as will be witnessed shortly.

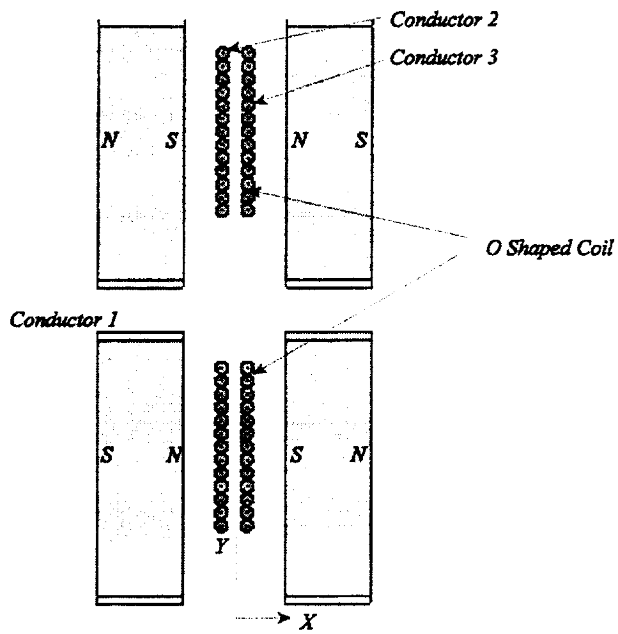


Figure 3 Null flux excitation (end view) acting against two "O" shaped coils.

The gap between magnets is 6.03 cm (2.375"). Of interest is the mutual inductance change as the guideway coils are displaced 1.52 cm (0.6") to the right. Treat the magnets as blocks with surface current on the sides. The mutual inductances M_{12} and M_{13} are shown in Figure 4. Since the guideway coils are displaced to the right, the right coil 3 continues to grow much more rapidly than the left coil coupling.

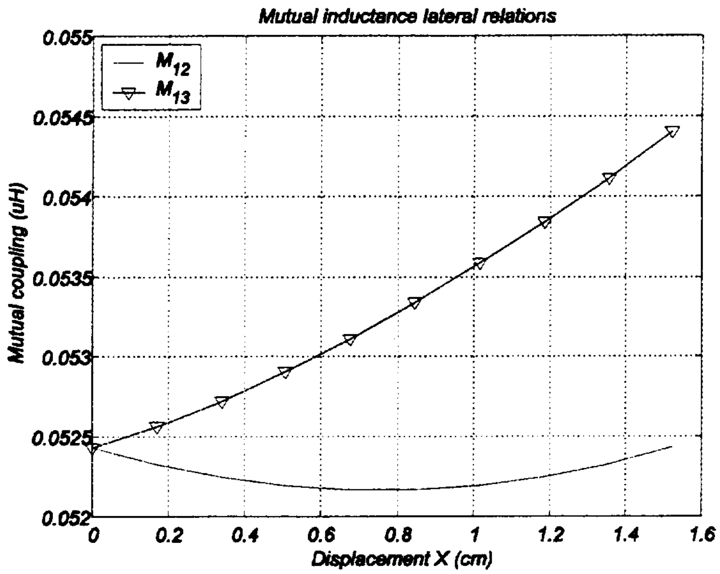


Figure 4 Mutual inductances M_{12} and M_{13} as a function of displacement.

If the coils are connected additively in series, the resultant coupling should be the sum of the two inductances in Figure 4. Conversely if they are connected to subtract in series, the mutual coupling should be the difference of these two quantities. A cross-connecting affecting this subtraction is not useful when the coils are in close proximity as they are here. Shown in Figure 5 are the results of these computations. As expected, subtracting the left and right mutuals results in a zero starting inductance, which grows with displacement.

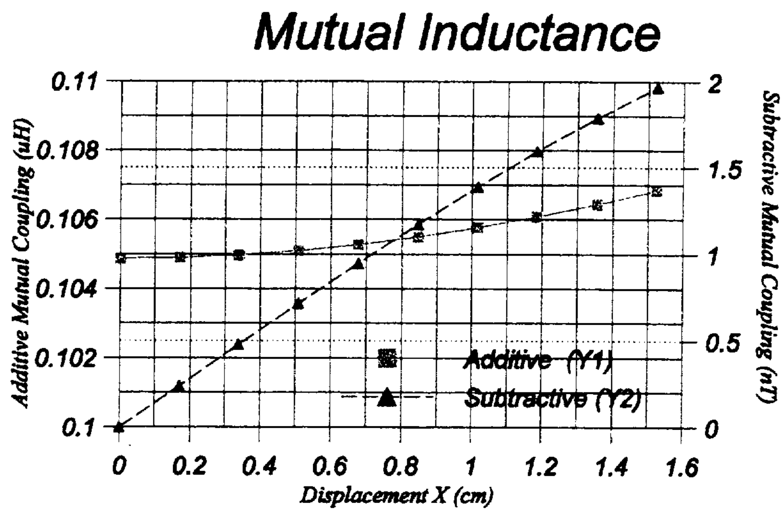


Figure 5 Mutual inductance when the left and right coils are connected additively in series versus subtractive.

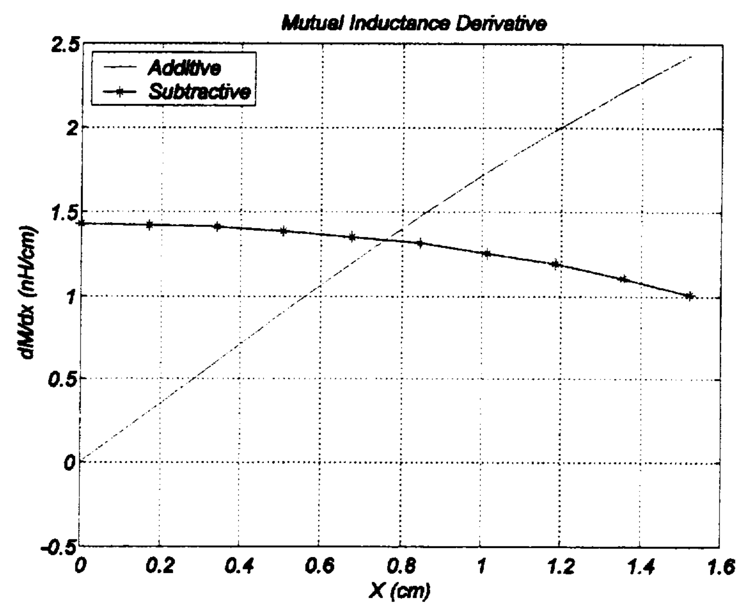


Figure 6 Mutual inductance derivative for additive and subtractive cross-connections.

Of central importance is the derivative of these inductances with displacement. X. This derivative is shown in Figure 6. The derivative of the subtractive curve is incorrect at x=0. The x=0 point corresponds to the top of a peak for which the derivative is actually undefined. But the value jumps immediately off the peak to a value superior to the additive cross-connection. What is more noteworthy is the fact that the additive cross-connection soon catches up and exceeds the subtractive cross-connection. No real advantage is gained by cross connecting the coils.

The analysis for lateral guidance parallels that for lift. The average x directed force is

$$\hat{F}_x = \frac{\Re}{2}\left[\frac{\partial M^*}{\partial x} I_1 I_2\right]. \tag{14}$$

The mutual coupling is written either as (1) or (2), and I_2 from (5) gives

$$\begin{bmatrix}\hat{F}_{xR}\\ \hat{F}_{xN}\end{bmatrix} = -\frac{\Re}{2}\frac{\partial M_0}{\partial x} I_1^2 \left(\frac{jM_0\omega}{j\omega L_2 + R_2}\right)\begin{bmatrix}\cos(\frac{\pi}{2h}y)\\ \frac{1}{2}\sin(\frac{\pi}{h}y)\end{bmatrix}. \tag{15}$$

The derivative $\frac{\partial M_0}{\partial x}$ scales with M_0 for either the rectangular or the null flux system. The all important ratio of these two forces becomes

$$\frac{\hat{F}_{xR}}{\hat{F}_{xN}} = \left(\frac{\cos(\frac{\pi}{2h}y)}{\frac{1}{2}\sin(\frac{\pi}{h}y)}\right)^2 \approx \begin{cases}\left(\frac{2h}{\pi y}\right)^2 \Big|_{small\ y}\\ 4\ \Big|_{at\ their\ maximum\ positions}\end{cases}. \tag{16}$$

A full coil rectangular excitation gains in lateral guidance exactly what it lost in drag. Since the rectangular excitation generates more lift, less units are required for levitation. But in addition to greater drag, the rectangular coil has another disadvantage, that of providing no restoring force to the vehicle should the vehicle be lifted by a gust of wind or in rising over the crest of a hill. The return path for the field also must be made in the z direction. This sometimes forces the use of more back iron for reasonably long pole pitches.

Is there a way to use the larger guidance force generated by the full rectangular coil? When the magnets are in repulsion as suggested in Figure 7, the mutual coupling for the coils themselves drops by an order of magnitude. When the fields repel one another, the drag induced will be much smaller since the mutual coupling is smaller. Note that this is a top view of the rectangular system, unlike Figure 3 in which an end view is pictured for the null flux magnets.

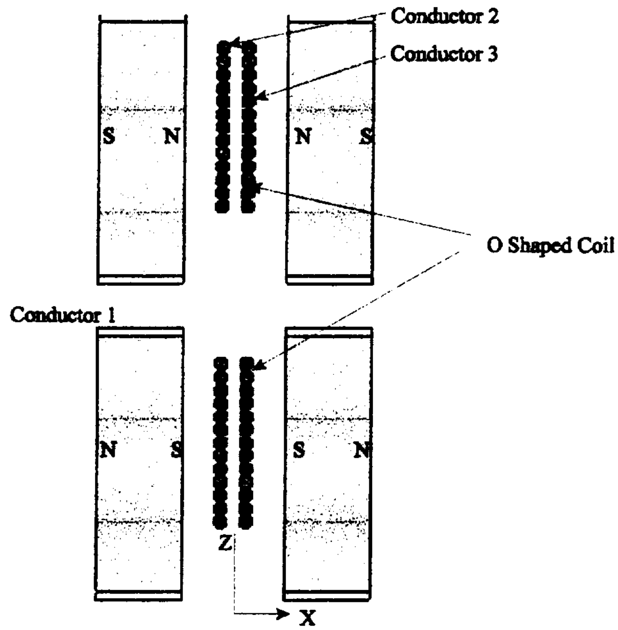


Figure 7 Guidance magnets (top view) are arranged in repulsion to minimize drag.

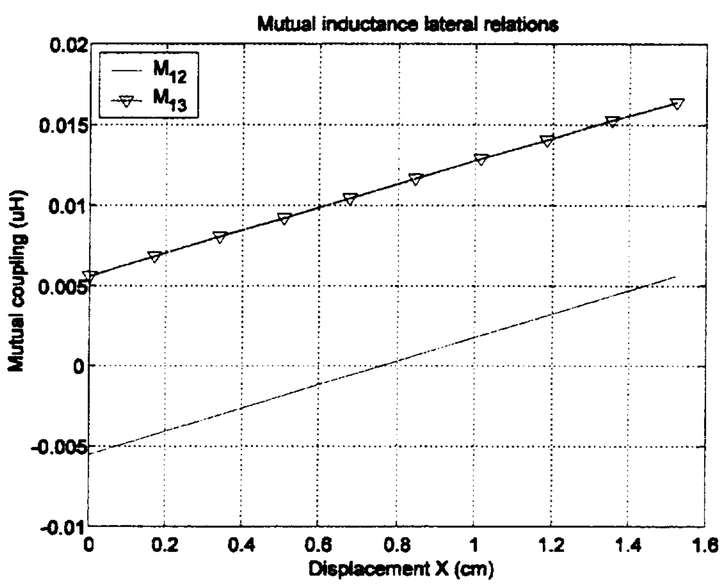


Figure 8 Mutual coupling M_{12} and M_{13} for a repulsive field arrangement.

For this repulsion arrangement the mutual coupling equivalent to Figure 4 results in the mutual coupling of Figure 8. Note that these mutual couplings are an order of magnitude smaller than those in Figure 4. But the rate of change of these quantities is also much larger.

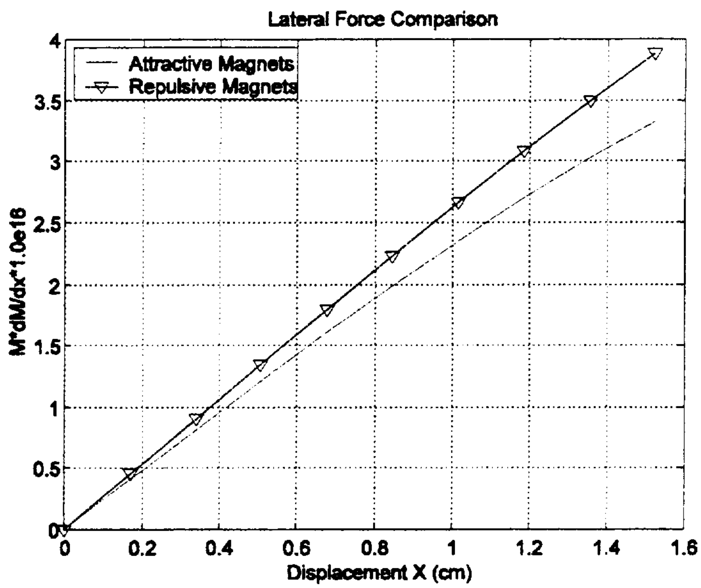


Figure 9 Comparison of the guidance force from repulsive and attractive magnets.

The actual number to compare, evident from (15), is the product $M\frac{\partial M}{\partial x}$. Figure 9 shows that the derivative more than makes up for the smaller mutual coupling, yielding a higher product. So a repulsive magnet arrangement has a small drag penalty, but yields a high guidance force. The optimal excitation appears to be a combination of these two excitations to get lift and drag simultaneously. The configuration shown in Figure 10 shows what may be the best combination.

Conclusions

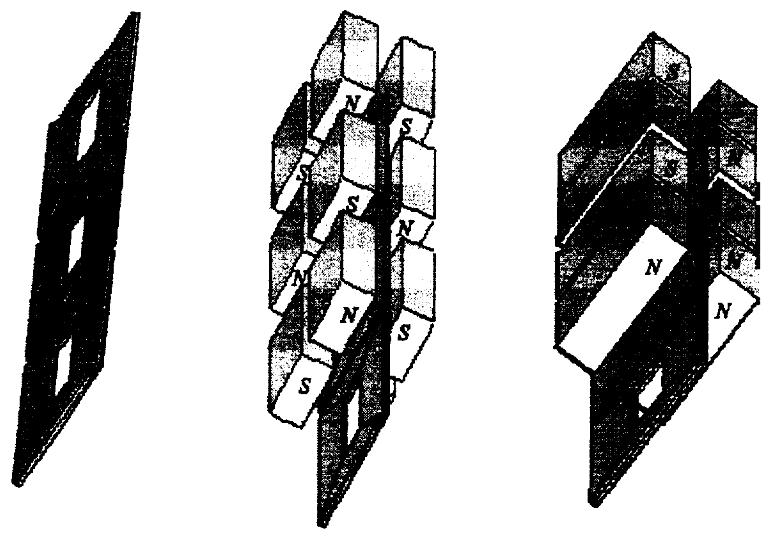
Null flux excitation systems are preferred over full coil excitation. Null flux coil excitation systems have the following advantages:

- Provision of lift force in both directions.
- Less drag.

The following disadvantages are also noted:

- Poor lateral guidance force production.
- Slightly smaller lift generation capability than a full coil excitation.

Both continue to improve their lift / drag ratio with speed. Drag force continues to decrease with speed. Attempting to cross-connect identical guideway coils is not an effective means of enhancing guidance forces. One effective means is to use full coil excitations oriented in repulsion. This arrangement has a smaller drag due to the diminished net coupling with the repulsion magnets. Excitation coils in repulsion yield the same guidance forces as attractive excitation coils, yet the former have less drag. The objective for lift or guidance is to maximize the mutual derivatives, and minimize the mutual inductance, since the latter contributes drag.



(a) Guideway Coils *(b) Lift Magnet Excitation* *(c) Guidance Magnet Excitation*

Figure 10 Using null flux magnets for lift and repulsive rectangular magnets for guidance appears optimal.

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