MAGNETICALLY BASED RIDE QUALITY CONTROL FOR AN ELECTRODYNAMIC MAGLEV SUSPENSION

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SUMMARY

ElectroDynamic Suspensions are highly undamped and require some form of active control or a secondary suspension to achieve adequate ride quality. This paper reports on efforts to develop a version of EDS that uses controllable magnetic forces to eliminate the need for any secondary suspension. The magnetic forces act directly on the guideway and avoid the need to have unsprung weight and a secondary suspension. It is shown that the energy required to effect this control can be less than 1% of the energy stored in the suspension magnets, so a modest size controller can be used. The same controller can also provide lift at very low speeds and thereby eliminate the need for a separate low speed suspension system.

INTRODUCTION

ElectroDynamic magnetic Suspension, called EDS and referred to as repulsive Maglev because it relies on repulsive magnetic forces, has the capability of allowing high speed transportation with a relatively large gap between the vehicle and guideway. In 1966 Danby and Powell proposed an EDS system using superconducting magnets with a "null flux" suspension that offered reduced magnetic drag. Subsequent researchers in the U.S., Japan, Germany, the UK and Canada have come up with a variety of further innovations, but there are still a number of technical problems that need resolution.

To date the only commercial Maglev implementations have used the electromagnetic suspension in which electromagnets support a vehicle with attractive force to a steel guideway. While EMS may be a preferred option for lower speed designs, it has the fundamental disadvantage of requiring a small gap between vehicle and guideway, typically less than a centimeter, and requiring active control to maintain the gap. The

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promise of EDS is that this gap can be increased by a factor of 5 or more, and therefore guideway tolerances are relaxed and cost might be reduced. Another purported advantage of EDS is that it can be inherently stable and not dependent on feedback to maintain a constant gap. Unfortunately this advantage is not as real as it appears because all EDS designs are highly underdamped and, in certain cases, even unstable. Other disadvantages of EDS are higher power requirements for suspension, higher external magnetic fields and the need for a separate low speed suspension system.

The foremost obstacle to installing any high speed ground transportation system is the high cost, but the key issue is the high cost of constructing a guideway, and this issue is not unique to Maglev. Many researchers are now convinced that, for new installations, if Maglev technology were fully developed it would be less expensive than a high speed train if all installation and operating costs are included. This is particularly true if the Maglev system can provide shorter travel times and more frequent service which, in turn, attracts more users so that the capital cost per user is reduced. The reason for the EMS preference has been its apparently lower cost because it uses a relatively simpler technology with fewer unknowns. German Maglev developers have shown that EMS can operate successfully at speeds over 400 km/h, so the problem is to improve EDS to the point that, for high speed travel, it has enough advantages to compete with both EMS designs and high speed rail.

We believe that in order to achieve wide acceptance EDS designers must face squarely the following problems:

- The cost of manufacturing and installing suspension and propulsion components on the guideway must be comparable to EMS designs;
- The suspension system must have a power loss that is comparable to power loss in EMS designs;
- All EDS suspension designs are highly underdamped and it is imperative to find practical means to damp oscillations and provide high ride quality;
- External magnetic fields associated with onboard superconducting magnets must be reduced, particularly in the passenger compartments.
- It is highly desirable to eliminate the need for a separate low speed suspension system because this adds to the cost, weight and complexity of both the vehicle and the guideway.
- Any superconducting vehicle magnets must be able to operate reliably in a hostile transportation environment.

This and two companion papers [19, 20] report the latest results of MIT research to develop an improved EDS design that addresses all of these issues.

SUMMARY OF PRIOR EDS STABILITY RESEARCH

The problem of stability has long been recognized as one of the fundamental design challenges for the successful commercialization of electrodynamic Maglev. The stability of Maglev vehicles is of considerable interest due to its effects on passenger safety and structural requirements. Many theoretical and several experimental studies have been done to illustrate this problem.

Woods et. al. [1970] considered the stability of a levitated superconducting current ring and evaluated passive damping techniques as well as active stabilization. Davis and Wilkie [1971], Fink and Hobrecht [1971], and Reitz and Davis [1972] studied the problem of infinitely-long wires traveling over an infinite conducting sheet and found vertical and transitional instabilities in the absence of air drag.

This problem of negative magnetic damping was studied by Yamada et. al. [1974] who built an experimental facility in 1973. A ferrite magnet was suspended and allowed to vibrate near a rotating aluminum drum. The damping behavior of the system was observed at various operating speeds, and it was found that negative damping exists for linear velocities above a critical velocity. For a full-scale train traveling over a sheet guideway, these results extrapolated to negative damping for train speeds higher than ~60 km/hour.

Iwasa [1973] and later Iwamoto et. al. [1974] applied the impedance-modeling method to predict lift and drag forces and to study the static and dynamic stability of various vehicle-guideway configurations. Iwamoto predicts a negative damping coefficient for train speed over ~50 m/sec traveling over a trace with discrete loops. Iwamoto recommends using passive damping to achieve good ride quality.

The conclusion of many of these early studies was that some form of damping is needed for acceptable ride quality, even in the presence of aerodynamic drag. Passive damping devices were considered, but the use of passive conducting plates or tuned coils between the lift magnets and the sheet guideway did not provide sufficient damping for the expected guideway roughness. It was concluded that some sort of secondary suspension or active control is needed.

The MIT team of Kolm, Thornton, Brown and Iwasa [1975] studied the stability of the EDS Magneplane system with a 1/25th-scale model, and found the suspension to be underdamped and prone to catastrophic accelerations. One important development for vertical control was the use of the linear synchronous motor for heave damping.

Later stability studies have focused on dynamic instabilities and the effects of mode coupling. Chu and Moon [1983], demonstrated instabilities in a 2 D.O.F. electrodynamic

Maglev model, showing limit cycle oscillations at operating speeds near the Maglev drag peak. Due to the small scale of their model, aerodynamics significantly affected their results. In other experiments, Moon [1977] reports results from a rotating wheel test facility for study of lateral, heave, roll, yaw, and pitch motions. A yaw-roll instability was observed.

The most detailed study of instabilities to date in EDS Maglev has been performed by the Maglev group at the Argonne National Laboratory [Chen, et. al, 1995], [Cai et. al, 1996]. Suspension instabilities of EDS systems with 3 and 5 degrees-of-freedom (D.O.F.) have been evaluated by computer simulation. Their results show that coupling effects among the 5 D.O.F. play an important role and that there are several potential instabilities. The instabilities depend on the equilibrium air gap, which in turn is determined by the vehicle mass, passenger load, and guideway design.

An active secondary suspension using high-temperature superconductors has been built and analyzed by the MIT group of Thornton and Thompson with help from Kondoleon and Draper Laboratory [1995-1997]. With scaling law studies and tests on a rotating test wheel facility, it was shown that it is possible to actively control the magnet position to achieve good ride quality with reasonable levels of power and energy from the control source.

It should be noted that many of the reported instabilities are related to the propulsion means. If a constant propulsive force is used, instability can arise because the magnetic drag decreases with increasing speed. In many cases the use of a constant speed propulsion, or the use of feedback control for the linear motor, would eliminate the instability.

THE PROBLEM OF RIDE QUALITY CONTROL

The Birmingham, England airport shuttle used only an active electromagnetic suspension and the combination of speed and air gap was such that no secondary suspension was required. The Birmingham system had a remarkably good record of reliability, and was advertised as having no moving parts except the doors! It is the goal of the work reported here to develop similar active suspension options for electrodynamic systems which, because of their larger air gap, have the potential to operate at high speeds.

A controllable magnetic primary suspension has a big advantage over an uncontrolled primary suspension combined with an active mechanical secondary suspension: the magnetic force acts directly on the guideway and does not require that there be any "unsprung" weight. EMS systems have the same advantage, but the air gap is so small that an active primary suspension has not been deemed sufficient to give adequate ride quality at high speeds. In 1972 an MIT research project demonstrated the ability of an LSM to produce controllable vertical forces on a Maglev vehicle, and this allowed the damping of heave motion [8]. By mounting the LSM in different configurations it is possible to counteract sway as well as heave, but since the force acts uniformly over the whole vehicle it is not possible to control pitch or yaw. Therefore, additional magnetic forces are needed to augment the LSM forces.

In principal one could directly control the current in the vehicles suspension magnets, but this is impractical because of the large energy storage associated with these magnets. This is particularly true of the most common design which uses a single array of low temperature superconducting coils without any ferromagnetic material in the flux path. Such designs have large external fields with a very large magnetic energy storage, and this energy must be changed relatively fast to provide good ride quality. Moreover, the low temperature superconducting wire can not tolerate large AC components of current without requiring very large refrigeration power to overcome the AC losses.

The design reported here incorporates three features, each of which contributes to making it feasible to construct a controllable magnetic suspension:

- The vehicle magnets use high temperature superconducting wire that is able to tolerate substantial AC current without excessive power loss;
- The vehicle magnets use an iron core which greatly reduces the amount of energy stored in the field;
- The suspension uses the flux canceling design for which a small differential magnetic field can produce a significant force.

Taken together, these features make it possible to have a reasonable amount of power control the ride quality for a suspension that can tolerate several centimeters of vertical motion.

A SIMPLIFIED MODEL OF FLUX CANCELING SUSPENSION

Prior publications and a companion paper [19] provide a detailed description of the Flux Canceling Suspension system, but for this paper we use the simpler model shown in Figure 1. This Figure represents the vehicle magnets by two wave windings and the guideway by a simple ladder. Each vehicle has two identical suspension systems, one on each side of the vehicle. The guideway can be a channel, with the guideway ladder mounted on the inside vertical walls of the channel, or the guideway can be a monorail, with the guideway ladder mounted on the outside of the monorail. The suspension forces are shear forces between the guideway and vehicle and any lateral forces are balanced by lateral forces on a separate suspension system on the other side of the vehicle. For this paper we only consider the suspension forces for a single system. The same ideas can be applied to control guidance forces, but guidance is not discussed in this paper.

In Figure 1 the heavier lines show the ends of two wave windings and the lighter lines show a guideway ladder. The two structures are laterally displaced by a distance that is much less than *h*, the height of the ladder. The actual vehicle magnets consist of windings on the poles of a ferromagnetic structure and the guideway uses more vertical members and a more elaborate arrangement in order to minimize unwanted eddy currents, but this simple model is adequate for the analysis of an active suspension system. The analysis assumes the vehicle is moving with respect to the guideway, so there is the potential for the vehicle to induce AC currents in the guideway and thereby produce vertical lift forces on the vehicle.

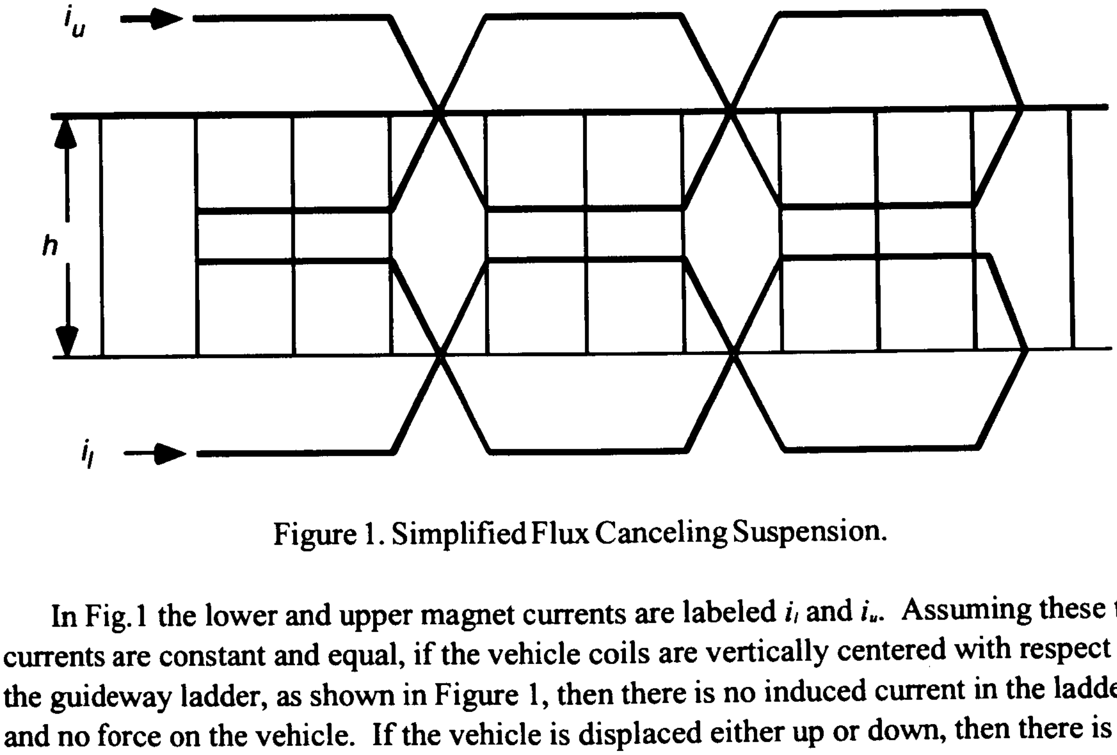

Figure 1. Simplified Flux Canceling Suspension.

In Fig. 1 the lower and upper magnet currents are labeled i_l and i_u. Assuming these two currents are constant and equal, if the vehicle coils are vertically centered with respect to the guideway ladder, as shown in Figure 1, then there is no induced current in the ladder and no force on the vehicle. If the vehicle is displaced either up or down, then there is an induced current that creates a restoring force; i.e. the suspension behaves like a magnetic spring. Note that even though there is considerable power loss in the guideway ladder, the suspension is undamped except for minor losses due to aerodynamic effects and eddy currents that are not represented in this simplified model.

The key to the analysis is to note the functional dependence of vertical force on currents. Although the currents in the rung and side elements in the ladder have a complex behavior, we can imagine a composite RMS current, called i_g, that characterizes the behavior. In order to simplify the analysis define sum and difference values of the vehicle coil currents. The sum i_s is the suspension current that is used to control the equilibrium position and the difference i_c is the control current that is used to control ride quality:

$$\begin{aligned} i_s &= i_l + i_u \\ i_c &= i_l - i_u \end{aligned} \tag{1}$$

If the vehicle is going fast enough to be on the high speed side of the drag peak, then we can express the effective guideway current as:

$$i_g = k_1\left(i_s y + i_c h_e\right) \tag{2}$$

where k_1 is a proportionality constant that depends on many details of the design, y is the vertical displacement of the vehicle from equilibrium, and h_e is an effective height that determines the induced voltage; in a typical design h_e is about $0.4h$, where h is the height of the guideway as shown in Fig. 1.

Given i_g we can express the vertical lift force F_y as:

$$F_y = k_2 i_g i_s \tag{3}$$

where k_2 is another proportionality constant that depends on the design details.

Define y_0 as the displacement y at equilibrium when the vertical force equals the weight of the vehicle, mg. Then, combining Eqs. 1 to 3 we have:

$$F_y = mg\left(1 + \frac{i_c h_e}{i_s y_0}\right) \tag{4}$$

We interpret Equation 4 as follows. If we wish to exert a control force, say a controllable force up to 0.2g, then we need to make the second term in parenthesis in Eq. 4 have a value of up to 0.2. For a typical full scale design $h_e = 0.2$ m and $y_0 = 0.1$ m, so the control current needs to be only about 10% as large as the suspension current. This 0.2g of control force is in addition to any force produced by the LSM, which can also be on the order of 0.2 g, either up or down. Since the vehicle is suspended by a long array of magnets, each can have its own control system, exactly as with EMS designs. Then it is possible to provide controllable pitch forces, and if the same ideas are applied to guidance it is possible to produce controllable yaw forces.

In order to control the ride quality we separate each of the wave windings in Fig. 1 into two equal parts and connect them in the bridge configuration shown in Fig. 2.

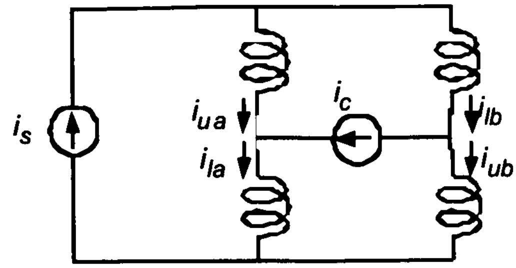

Figure 2. Bridge connection of vehicle windings.

The suspension current i_s excites the bridge so as to control the sum of the magnet currents and the control current i_c excites the bridge so as to control the difference of the magnet currents. In this way we have a simple way to provide only the differential current required for ride quality control.

An important point to note is that there are mutual inductances between the various coils in Fig. 2, and the inductance seen by the suspension current source is typically about twice as large as the inductance seen by the control current. This reduction in control circuit inductance reduces still further the power and energy needs to effect ride quality control. In short, it takes less than 1% as much energy to effect a 0.2 g control force as it does to provide the equilibrium suspension force. For a typical design the power and energy required for good ride quality can be less than the power and energy required to control the magnets in an EMS system.

Experimental results to substantiate this type of control are reported in companion papers in these proceedings [19, 20] and in more detail in an MIT thesis [18].

ZERO SPEED SUSPENSION

The ride quality control hardware can also be used to effect suspension at zero speed. To do this the control current is connected so as to only excite the upper magnet current in Fig. 1. The controller then applies a low frequency sine wave, on the order of 10 Hz, and this induces AC current in the guideway and produces lift. When the vehicle is resting on the guideway the displacement from equilibrium is relatively large so that by exciting only the upper magnets a large current is induced in the guideway ladder. In practice a multiplicity of controllers would be used, each driving only a single magnet, and the excitation currents would be phased so as to minimize pulsating forces. This means of supplying zero speed lift would produce excessive power loss in the guideway if allowed to persist, but in practice it would only be used for a few seconds until the vehicle speed is past the drag peak. With the suspension system described in this paper the drag peak can be less than 10 m/sec and when this transition speed is reached the normal EDS mode would be activated.

Preliminary experiments have been done to prove the feasibility of low speed lift, but more work is needed to design a working system.

CONCLUSIONS

When an EDS system is built with a Flux Canceling suspension using iron core magnets and high temperature superconducting wire, it is possible to use magnetic forces to control ride quality and eliminate the need for a secondary suspension. This same system can also be used to provide zero speed lift and eliminate the need for a separate low speed suspension system. More work is needed to optimize the design, but initial experiments are very encouraging.

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