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A Review of Dynamic Stability of Repulsive-Force Maglev Suspension Systems*

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Abstract

This paper summarizes and discusses the results of work, published over the past 25 years, that is pertinent to the problem of understanding the factors influencing the dynamic stability of repulsive-force maglev suspension systems.

Introduction

Vehicle dynamics and the need to satisfy ride quality requirements have long been recognized as crucial to the commercial success of passenger-carrying transportation systems. Design concepts for maglev systems are no exception. Early maglev investigators and designers were well aware of the importance of ride quality and took care to ensure that their designs would meet acceptable ride quality standards. More recently, the System Concept Definition program, sponsored under the auspices of the U.S. National Maglev Initiative, required concept designers to meet a detailed set of ride quality specifications (Coltman, 1992).

In contrast, the dynamic stability of electrodynamic suspension (EDS) systems, which has obvious implications for system safety and cost as well as for ride quality, has not received nearly as much attention. This may be due in part to the difficulty of conducting sufficiently accurate computer simulations, or to the incapability to sort out the many complex factors that influence the dynamics of magnetically suspended vehicles on test tracks. Because of the well-known under-damped nature of EDS suspension systems and the observation of instabilities in laboratory-scale model systems, it is prudent to develop a better understanding of vehicle stability characteristics. It is hoped that such an understanding will lead to improved suspension systems and better control laws to ensure a high level of ride comfort and safety.

EDS systems are often thought to be inherently stable. This is generally true under static or steady-state conditions. However, under the influence of nonsteady-state conditions, it is found that depending on various factors, including the nature and extent of active or passive damping mechanisms incorporated into the design, perturbations may lead to stable or unstable motions.

The work reported in this was undertaken with the intention of summarizing information that has been accumulated worldwide and that is relevant to dynamic stability of repulsive-force maglev suspension systems, assimilating that information, and gaining an understanding of the factors that influence that stability. Included in the paper is a discussion and comparison of results acquired from some representative tests of large-scale vehicles on linear test tracks, together with analytical and laboratory-scale investigations of stability and dynamics of EDS systems.

This paper will also summarize the R&D activities at Argonne National Laboratory (ANL) since 1991 to study the nature of the forces that are operative in an EDS system and the dynamic stability of such systems.

Tests of Dynamics of Large-Scale Vehicles on Linear Test Tracks

Early tests of EDS-type maglev systems that employed either continuous-sheet (see e.g., Coffey et al., 1972, 1973, 1974a, 1974b, 1974c; Iwahana et al., 1980) or discrete-coil guideways (references cited below) demonstrated stable performance. Neither the tests nor analytical calculations exhibited instabilities during the tests performed by Coffey et al. and Iwahana et al.

Using discrete-coil guideway systems, the Japanese ran tests on various EDS-type systems at the Miyazaki test track starting in the late 1970s. The first configuration was an inverted T-shaped guideway that consisted of horizontally mounted ground or lift coils and vertically mounted propulsion and null-flux guidance coils. This structure was straddled by the 10-metric-ton (mt) MLU-500 vehicle that carried separate lift and propulsion superconducting magnets (SCMs) mounted on an inverted-U-shaped support structure. Data on vehicle dynamics were reported in the range of ≈21 m/s to 83 m/s (Yamashita, 1978). The amplitude of all modes decreased with increasing speed throughout the reported speed range and no instabilities were evident.

In the 1980s, the Miyazaki system was changed to a U-shaped guideway, with horizontally mounted lift coils and sidewall-mounted propulsion and guidance coils. The three-vehicle set (designated MLU-001) fit inside the U-shaped guideway and carried SCMs mounted vertically. In spite of a resonant condition near 83 m/s, the suspension system was robustly stable (Tanaka, 1982; Sato et al. 1985).

In 1987, the new 17-mt MLU-002 vehicle came on line at Miyazaki. The suspension magnets in this new vehicle were at the front and rear of the vehicle, not distributed along its length as in the MLU-001 series (Fujie, 1989). No instabilities have been reported for the MLU-002 although other problems were experienced, including noticeable yaw motion above the lift-off speed (Rote, 1989) and, near maximum speed, magnet quenches caused by excessive heat generated by the combined mechanical and electromagnetic resonance. In 1993, the Japanese introduced a modified vehicle, the MLU-002N, that alleviated the magnet quench problem and permitted testing at up to ≈120 m/s (Masada, 1993, 1995; Nakashima et al., 1993). In this modified vehicle, the guideway lift conductors were changed from horizontally mounted single-coil type to sidewall-mounted null-flux type. Again, no instabilities were reported.

Analytical and Laboratory-Scale Investigations of Stability and Dynamics of Magnetically Suspended Systems

Early analytical studies of idealized systems and experiments with small-scale models demonstrated that magnetically levitated and guided systems were intrinsically underdamped against perturbations and formed unstable equilibrium states (Davis and Wilkie, 1971; Fink and Hobrecht, 1971; Moon, 1977; Kolm and Thornton, 1973; Borcherts, 1982). An excellent discussion of maglev system dynamics and stability is given in a recent book by Moon (1994).

It is well known that the induced eddy currents that produce the levitating force also give rise to the electromagnetic (EM) drag force that must be overcome by a propulsion motor. Inasmuch as this drag force decreases with speed above the peak of the EM drag force, it is natural to expect that the intrinsic magnetic damping of motions in various directions would also decrease with the speed of the motions and, as a consequence, result in underdamped motion or instability (Davis and Wilkie, 1971; Fink and Hobrecht, 1971).

Ohno et al. (1973) studied the pulsating lift forces in a linear synchronous motor and found that these lift forces may cause parametric and combination resonances in addition to heaving and pitching oscillations.

Experiments on the Massachusetts Institute of Technology (MIT) magneplane model system (Kolm and Thornton, 1973) showed obvious evidence of dynamic instability that was recorded on film in the early 1970s.

Much later, in a memorandum, Kolm (1993) commented that "EDS suspensions are inherently stable, but they are also inherently underdamped, and are susceptible to catastrophic oscillations, particularly in rectangular trough configurations." He noted that in the first series of tests at the MIT Francis Bitter Laboratory, a 1/25th-scale magnetically suspended vehicle was towed through various guideways. In the case of a rectangular guideway, the vehicle "...often reached a limiting velocity and then fishtailed along the remaining guideway. Occasionally, the oscillations increased to catastrophic amplitude, causing wall-scraping and even derailment." He explained that the large-amplitude motions were the result of a drag-force-induced yaw instability.

It is plausible that the drag-force-induced instability that Kolm spoke of would not necessarily be seen in tests on large-scale vehicles. This follows from the facts that the large-scale test vehicles included a substantial amount of enhanced passive damping and that the tests were performed mostly above the drag peak, and it follows especially if they also were subject to strong, nonlinear guidance forces that could effectively limit lateral motion. This line of reasoning is consistent with the observation that the lift-off speed of the Japanese test vehicles at Miyazaki is surprisingly high (≅50 m/s). It was reported to one of the authors of this paper that the reason for this high lift-off speed was insufficient guidance force at lower speeds (Rote, 1993).

In 1974, Moon observed that an experimental vehicle model with three degrees of freedom (DOF), floating above a large rotating wheel with a "V"-shaped aluminum rim, exhibited a lateral-roll-yaw instability. Later, Moon (1978) noted that "While full-scale tests have yet to report such instabilities, laboratory model tests of fully levitated and guided models have shown that they can occur under a broad range of guidance track configurations and magnet and vehicle geometries." He and other authors noted that intrinsic magnetic damping has been shown to decrease with speed and can become negative, leading to self-excited vehicle oscillations (Moon, 1977; Davis and Wilkie, 1971; Iwamoto et al., 1974; Yamada et al., 1974).

Davis and Wilkie (1971) showed analytically that in the absence of other damping mechanisms and coupling to other modes, this negative intrinsic magnetic damping gives rise to an unstable lift force between a moving current-carrying wire and a conductor sheet.

Subsequently, the Ford Motor Co. team (Davis et al., 1972) conducted further analytical studies of damping and examined passive damping mechanisms as well. Later, these studies were refined and laboratory experiments on the effects of passive and active damping were carried out by Reitz et al. (1973). Davis et al. (1972) and Reitz et al. (1973) concluded that placing passive conducting plates or tuned coils between the lift magnets (fixed to the magnets) and a sheet guideway did not provide sufficient damping to give acceptable ride quality for the expected guideway roughness. Therefore, it was concluded that either a secondary suspension system or some form of active control was needed. In their final report (Philco-Ford Corp., 1975), the Ford team concluded that "for realistic guideway roughness levels, the suspension is not sufficiently soft to meet the ride quality standards without damping, and since there is very little inherent damping in the system, some form of external damping must be provided."

Fink and Hobrecht (1971) analyzed the case of an infinitely long current loop moving parallel to a conductor sheet with the velocity perpendicular to the length of the loop. They found that all equilibrium positions of the loop were unstable under linear and angular perturbations.

Yamada et al. (1974) were apparently the first investigators to demonstrate the phenomenon of negative intrinsic damping experimentally. They used a pendulum that consisted of a small magnet array supported by a string. The magnet array was free to move normal to the surface of a rotating aluminum cylinder. They reported that, after accounting for aerodynamic and mechanical drag, the remaining drag force was positive at very low rotor speeds and was negative at high rotor speeds.

Moon (1977) reported on a similar experiment, and found that the intrinsic negative damping occurred at speeds higher than a critical velocity.

In his 1978 paper, Moon reported on a laboratory experiment in which he simulated, with a rotating-wheel apparatus, the inverted-T-shaped guideway used at Miyazaki in the late 1970s. Two parallel rows of short aluminum segments with L-shaped cross sections were mounted around the rim of the wheel. Eight lift and eight guidance permanent magnets were mounted on small model vehicles. Yaw lateral flutter-limit-cycle oscillations and pitch-yaw limit-cycle flutter were observed to occur in vehicles with certain inertial geometries. Moon (1978) appears to have been the first investigator to identify these complex limit-cycle oscillations in magnetically suspended systems.

Fujiwara (1980) reported the results of calculations and an experimental study of magnetic damping. Both his analytical and experimental results showed that as the velocity increased, the net magnetic damping force first decreased to a minimum but positive value (in the range of 11-17 km/h) and then increased. When the damping plate was removed, the velocity dependence of the net damping force remained the same, but was reduced by a factor of ≈ 2. It was further reduced when the damper coils were removed. Under the latter conditions (no enhanced passive damping with the possible exception of that from the cryostat walls and SCM windings), a difference was observed between the cases where the two SCMs had the same and the opposite polarities. For the same polarity case, the net damping force actually became negative in the calculations but not in the experimental results.

More recently, Fujiwara and Hariyama (1983) conducted additional tests, with a modified rotating apparatus in which they suspended four SCMs in a cryostat above a turntable that contained track coils. They investigated the relative contributions of the guideway coils, a damper sheet, and a thermal shield plate to damping. Without the damper sheet and with alternating polarity, they observed that the net damping force increased from a small negative value at ≈ 11 m/s to increasing positive values for speeds >17 m/s.

Andriollo et al. (1995a, 1995b) investigated the transient stability of EDS systems both analytically and numerically. They concluded that in EDS systems, the transient stability is affected by the electrical and geometrical parameters of both the on-ground levitation coils and the on-board excitation coils, as well as by the mechanical parameters of both the vehicle and the suspensions between the bogies and the vehicle. Under certain conditions, transient oscillations due to a motion perturbation could increase and lead the vehicle to instability.

Nature of the Magnetic Forces and Vehicle Dynamics Work at ANL

The objective of the R&D program on dynamic stability of maglev systems at Argonne National Laboratory (ANL) since 1991 (Coffey et al., 1991; Chen et al., 1992, 1993; Cai et al., 1992a, 1992b, 1992c, 1993a, 1993b, 1996; Cai and Chen, 1993, 1995a, 1996, 1997; He et al., 1994; Zhu et al., 1994) has been to develop a general approach to investigating and predicting the occurrence of instabilities in maglev suspension systems and to provide a better understanding of the conditions (design features and parameter values) that can lead to dynamic instabilities.

Analysis of Magnetic Forces

Magnetic forces are needed for any analysis of vehicle dynamics, design of guideway structures and fastening, and prediction of ride quality. These force components are considered here from the standpoint of vehicle stability. As a significant part of ANL's maglev R&D program, magnetic forces of a permanent magnet moving over an L-shaped aluminum sheet guideway were measured experimentally with a quasistatic method (Cai et al., 1996).

The experiment was conducted at ANL to investigate the lift, drag, and guidance magnetic forces that act on an NdFeB permanent magnet that is moving over an aluminum (6061-T6) L-shaped ring mounted on the top surface of a 1.2-m-diameter rotating wheel. For a given rotating speed of the wheel (ranging from 0 to 600 r/min, 0 to 37.7 m/s), the lift, guidance, and drag magnetic forces were measured while the guidance gap and lift height were varied.

The measured magnetic forces were compared with magnetic forces calculated by various computer codes.

Analysis of Motion-Dependent Magnetic Forces

The major components of the magnetic forces acting in an EDS system are position and velocity dependent. In addition, there are also force components that depend on the nature and extent of nonsteady state motions (Chen et al., 1993). The most significant motion-dependent force is the intrinsic magnetic damping force, which depends on the direction, magnitude, and time derivatives of the nonsteady-state motion.

With continuous-sheet guideways, motion-dependent magnetic forces are obtained mainly from experimental measurements (Chen et al., 1993; Zhu et al., 1994). Experimental results indicate that negative magnetic damping will develop once the characteristic speed is exceeded. This finding suggests that, in a continuous-sheet maglev system, instability will occur when the damping value becomes negative unless enhanced active or passive damping mechanisms are present. A computer model simulation of magnetic damping forces in a one-dimensional discrete-coil suspension system confirmed the existence of a negative damping phenomenon (He et al., 1994). More recently, in a modeling study of the proposed maglev upgrade of the rocket sled at Holloman AFB, He and Coffey (1997) showed that the passive magnetic damping due to two coils placed on board between the SCMs and the null-flux guideway coils is maximal at the null-flux position and decreases with the velocity of the motion perpendicular to the main vehicle motion.

Analytical and Numerical Studies

At ANL, Cai et al. (1993a, 1993b) and Cai and Chen (1995b) analyzed the dynamic instabilities of an EDS-type maglev system. Both analytical and numerical approaches were used, and various magnetic suspension forces, compiled from experimental data, were incorporated into the theoretical models. Divergence and flutter were obtained from analytical and numerical solutions for the coupled vibration of a three-DOF maglev vehicle model (Cai et al., 1993a, 1993b; Cai and Chen, 1995b). A computer code was developed to numerically simulate the dynamic stability of the five-DOF vehicle model, and extensive computations were performed with various parameters to determine the stability characteristics of EDS-type maglev systems. Instabilities of five directions of motion (heave, slip, roll, pitch, and yaw) of the dynamic vehicle model were predicted and it was demonstrated that system parameters, such as system damping, vehicle geometry, and coupling effects among five different motions, play very important roles in the occurrence of dynamic instability in maglev systems (Cai et al., 1993a; Cai and Chen, 1995b).

Stability Experiments

Two series of experiments were conducted on the dynamic stability of laboratory-scale model vehicles that were magnetically levitated and guided over a double L-shaped aluminum sheet guideway mounted around the rim of a rotating wheel (Cai et al., 1995, 1996). In Test A, a vehicle model was supported by four permanent magnets on four corners, whereas in Test B, four magnets for levitation and an additional four magnets for guidance were attached to the vehicle. The vehicle models were free to move in five modes (vertical heave, lateral slip, pitch, yaw, and roll). The longitudinal motion was constrained by a tether. The motions of the vehicles were measured during experiments in which the rotating speed of the wheel was varied. The system's stability was characterized by a surprising lack of robustness. Various complex motions and instabilities were observed during the experiments. One feature of the experimental apparatus, which made interpretation of the experimental results uncertain (particularly at low speeds) was the fact that the wheel was not a true cylinder of rotation. Small variations in the radius of the guideway surface as a function of angle and axial position caused excessive disturbances in the vehicle's motion near the lift-off velocity, where the air gap was approximately the same size as the out-of-roundness of the wheel.

Typical experimental results from Case 1 of Test A, shown in Fig. 1, revealed that (1) when the wheel speed was <6 m/s, the vehicle was unstable, with high-frequency (flutter) that may have been caused by wheel out-of-roundness. (2) When the speed was between 6 and 13 m/s, the vehicle was stable, and amplitudes of displacement and force were relatively small. (3) When the speed was between 13 and 30 m/s, the vehicle was unstable and dominated by vertical, slide, and yaw instabilities. (4) When the speed was >30 m/s, the vehicle was unstable in almost every direction and the oscillation amplitudes in five directions increased significantly.

Conclusions

• For safety, maglev systems should be stable. Because dynamic instabilities are not acceptable for any commercial maglev system, it is important to consider these instabilities when designing and developing maglev suspension systems.

• Motion-dependent magnetic forces, as well as other forms of damping forces, are important elements in modeling and understanding dynamic instabilities of maglev systems. At this time, it appears that very limited data are available for motion-dependent magnetic forces. The accurate prediction of damping forces still presents a problem. The existence of negative intrinsic magnetic damping appears to be firmly established. However, the impact of

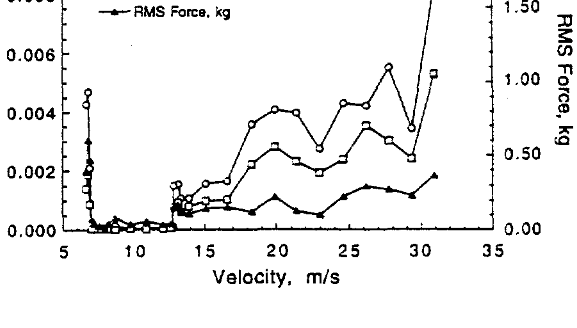

Fig. 1. Experimental results from Case 1 in Test A.

this phenomenon on large-scale systems that contain abundant sources of enhanced damping appears to be negligible. Efforts should be made to compile analytical results and experimental data for motion-dependent magnetic forces and vehicle dynamic stability. In his recent book, Moon (1994) stresses the need for analyzing the dynamic stability of large-scale vehicles including the effects of aerodynamic forces.

• Various methods can be used to stabilize a maglev system: passive electrodynamic primary suspension damping, active electrodynamic primary suspension damping, passive mechanical secondary suspension, and active mechanical secondary suspension. With a better understanding of vehicle stability characteristics, a better control law can be adopted to ensure a high level of ride comfort and safety.

• Comprehensive computer programs are needed to screen new system concepts, evaluate various designs, and predict vehicle response. The computer codes be capable of simulating extensive nonlinear-dynamic simulation of maglev systems and predicting maglev system performance.

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