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EMS Maglev Vehicle-Guideway-Controller Model

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Introduction

Computer simulation studies are a useful means to investigate the safety and performance of a high-speed magnetically levitated (maglev) vehicle negotiating an elevated guideway. These studies confirm the importance of accounting for the dynamic interaction that couples the vehicle and guideway. The vehicle and guideway systems are driven by the same action/reaction magnet force inputs specified by a controller. The controller's task is to dynamically adjust these force inputs to maintain a nominal gap between the vehicle and guideway (to prevent contact and robustly accommodate disturbances) while achieving satisfactory ride quality for passengers.

The critical components of the dynamically interacting system are the vehicle, guideway, and controller. This paper presents a summary of recent activities at CMRI to formulate analytical models of each of these components and conduct computer simulation studies of an electromagnetic suspension (EMS) maglev system.

Vehicle, Guideway, Controller Models

As indicated in the simplified block diagram of Figure 1, the vehicle is driven by forces ($\underline{f}$) generated by magnet modules on the vehicle. The guideway geometry disturbances to the vehicle include random irregularities ($\underline{d}$) and deterministic deflections ($\underline{w}$). The guideway random irregularities are the result of guideway geometry errors such as pier height variations, guideway misalignments, and surface roughness. The deterministic deflections are due to guideway dynamics excited by magnet forces. The total magnet force at each module consists of a perturbation force, varied by the controller, plus a steady-state force ($\underline{f}_0$) to maintain static equilibrium. The input to the controller is the gap error obtained by measuring the actual gap ($\underline{g}$) and comparing it with the desired nominal gap ($\underline{g}_0$).

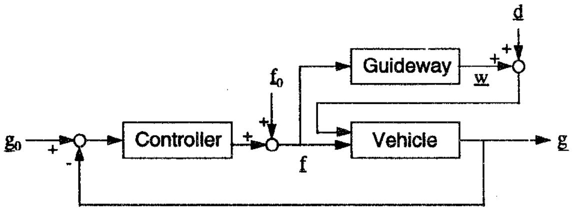

Figure 1. EMS Maglev System Configuration

The vehicle is assumed to incorporate an EMS system with magnet modules that are canted along the vehicle to provide simultaneous guidance and levitation by attractive forces. This design has been proposed by Grumman to achieve the necessary lateral and lift force components from the same magnet modules.

For studying vehicle dynamic behavior due to interaction with the guideway, a hierarchy of increasingly complicated vehicle models can be identified. For example, a simple model considers a single rigid carbody with four degrees-of-freedom (DOF), namely lateral, vertical, pitch and yaw. Here, it is assumed that the vehicle is traveling at constant speed on a straight, level guideway. A second model adds a roll DOF to the first model for a five DOF rigid body model. Subsequent models incorporate carbody flexibility, accounting for vertical and lateral bending modes and torsional modes. In this manner, simple to complicated vehicle models can be studied in progression, and distinguishing features can be highlighted.

A similar progression can be proposed for the guideway with a first model representing a straight, level, rigid guideway and subsequent models involving flexible multiple spans. A second model assumes spans that exhibit vertical bending modes and have pinned ends, a third model adds torsional modes to the second model, a fourth model considers other boundary conditions such as free ends supported by viscoelastic elements, a fifth model accounts for banked, curved spans, etc. Although, in theory, the guideway dynamic response is made up of an infinite number of mode shapes, generally only a few modes are included. In the study reported below two mode shapes are assumed for each span of the guideway.

A sequence of controller models for EMS-type maglev designs can be identified. Candidate controllers include a PD (proportional-plus-derivative) controller, equivalent to a stiffness-damper combination, a linear optimal controller (that assumes a performance measure reflecting gap error, magnet force variation, and carbody acceleration), and different nonlinear controllers, from gain-scheduled linear controllers to those reflecting full nonlinear, adaptive strategies. The long-term focus of work at CMRI is aimed at exploring the efficacy of different controller strategies.

Controller Design

The total magnet force acting at each module is due to a superconducting coil and a normal control coil. The superconducting coil provides the magnet force to support the vehicle in static equilibrium. The control coil generates the perturbation force; the control coil current is specified by a control law which drives the magnet module to restore the gap to its nominal value. By tuning the gains of the selected control law, the response may be adjusted to meet design requirements such as gap tolerance and ride quality.

Using classical control concepts, a PD controller law can be designed for each magnet module of a linearized maglev system. The plant of the linearized maglev system is a 4 DOF vehicle model which is cascaded with the PD controller to form the overall closed-loop control system. The inputs of this closed-loop system are the guideway displacements (in the gap directions) of 24 magnet modules, assuming 12 on each side; the outputs of the closed-loop system are the vehicle displacements (in the gap directions) of the 24 magnet modules. This multi-input, multi-output (MIMO) control problem can be solved for values of proportional gain (k_p) and derivative gain (k_d) at each module that satisfy design specifications. An underlying premise is that all magnet modules employ the same PD controller.

A set of specifications suggested in Grumman's magnet servo model [1] is adopted here. The design requirements consist of a damping ratio of 0.707 and a bandwidth of 10 Hz for the closed-loop system with guideway and vehicle displacements as input and output, respectively. A damping ratio of 0.707 ensures system stability and a fast response with moderate overshoot for gap error regulation. A bandwidth of 10 Hz promises adequate tracking at low frequencies and attenuation of gap errors due to guideway disturbances at higher frequencies (*i.e.*, higher than 10 Hz.) We have found it useful to generate contour plots of the damping ratio and the spectral norm of the closed-loop system at 10 Hz to determine these gains and understand the performance specification tradeoffs.[1]

Simulation Studies

A 5 DOF nonlinear maglev model was used to test the effectiveness of the tuned PD control law. In the simulation studies, the vehicle negotiates a multi-span guideway at 300 km/h for 100 m. A versine geometry error (0.01 m lateral offset over 5 m wavelength) is imposed at the beginning of the first span of an otherwise straight, level guideway. Preliminary investigations with representative parameter values for the vehicle and guideway suggest that the PD design meeting the posited specifications does not yield adequate performance.

Additional information is required to establish appropriate design specifications and to ensure practicality. Ultimately, this information can be used to specify maximum magnet force and force rates (or, with an appropriate magnet model, maximum current and current rates), gap errors for safe operation, bounds on lateral and vertical acceleration for acceptable ride comfort, and control system bandwidth, as well as other specifications.

Continued investigations of actively controlled maglev suspension models are underway. Optimization techniques are being applied in tuning the gains of PD and LQ control laws. The optimization problem being formulated minimizes the vehicle acceleration (to achieve acceptable ride quality) subject to constraints on gap error tolerance and magnet force variation.

Reference

[1] R. Gran, M. Proise, "Five Degree of Freedom Analysis of the Grumman Superconducting Electromagnetic Maglev Vehicle Control/Guideway Interaction," Maglev 93 Conference, Argonne National Laboratory, Paper No. PS4-6, May 19-21, 1993.

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[1] The spectral norm, i.e., maximum singular value, of the closed-loop transfer function matrix is related to the bandwidth; for example, the spectral norm at 10 Hz is equal to 0.707.