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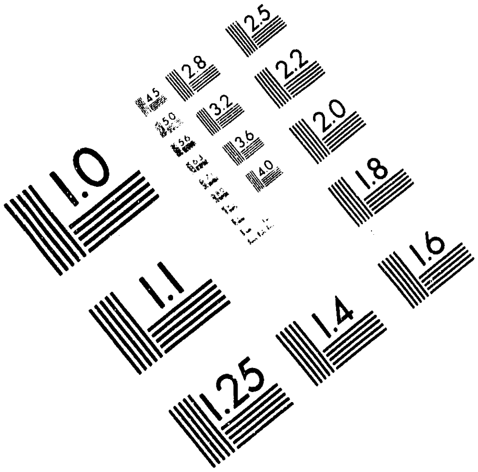
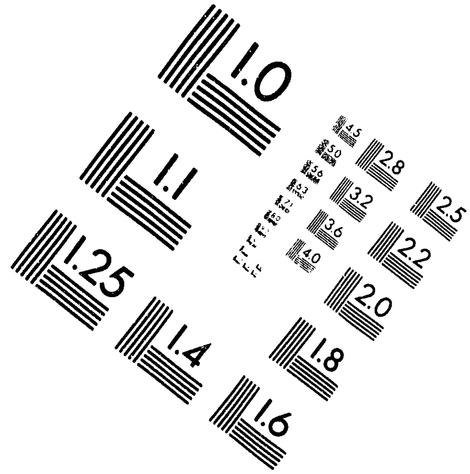

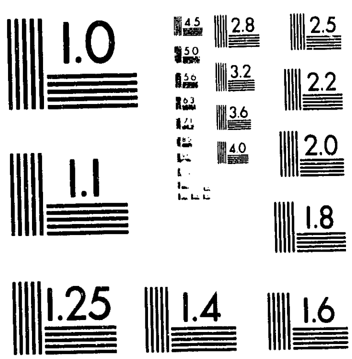

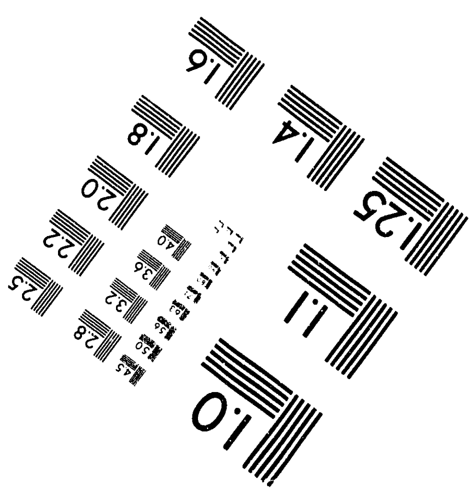
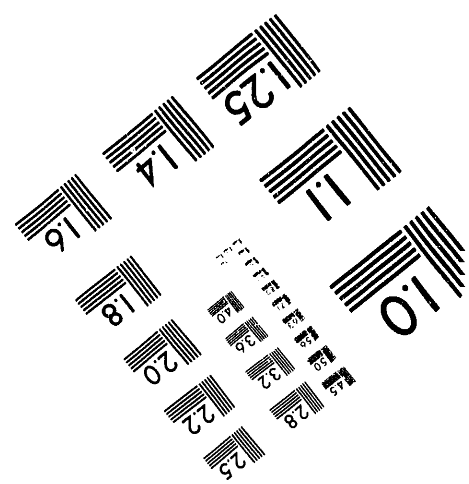

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Dynamics, Stability, and Control of Maglev Systems*

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Presented at "Maglev '93," Argonne National Laboratory, Argonne, IL, May 19–21, 1993.

*This work was performed under the sponsorship of the U.S. Army Corps of Engineers and the Federal Railroad Administration through interagency agreements with the U.S. Department of Energy.

Dynamics, Stability, and Control of Maglev Systems

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Abstract - **The vehicle/guideway interaction and ride quality, active and semiactive suspension control, and stability analysis are summarized for maglev systems.**

I. Introduction

The dynamic response of maglev systems is important in several respects: safety and ride quality, guideway design, and system costs. The dynamic response of vehicles is the key element in the determination of ride quality, and vehicle stability is one of the important elements relative to safety. To design a proper guideway that provides acceptable ride quality in the stable region, the vehicle dynamics must be understood. Furthermore, the trade-off between guideway smoothness and the levitation and control systems must be considered if maglev systems are to be economically feasible. The link between the guideway and the other maglev components is vehicle dynamics. For a commercial maglev system, vehicle dynamics must be analyzed and test in detail.

This paper is a summary of our previous work on dynamics, stability and control of maglev systems [1-7]. First of all, the importance of dynamics of vehicle/guideway of maglev systems is discussed. Emphasis is placed on the modeling vehicle/guideway interactions of maglev systems with a multicar, or multiload vehicle traversing on a single or double-span flexible guideway. Coupled effects of vehicle/guideway interactions in wide range of vehicle speeds with various vehicle and guideway parameters for maglev systems are investigated [1-4].

Secondly, the alternative control designs of maglev vehicle suspension systems are investigated in this study to achieve safe, stable operation and acceptable ride comfort requires some form of vehicle motion control. Active and semi-active control law designs are introduced into primary and secondary suspensions of maglev vehicles [3,7].

Finally, this paper discusses the stability of maglev systems based on experimental data, scoping calculations, and simple mathematical models. Divergence and flutter are obtained for coupled vibration of a three-degree-of-freedom maglev vehicle on a guideway consisting of double L-shaped aluminum segments. The theory and analysis developed in this study provides basic stability characteristics and identifies future research needs for maglev systems [5,6].

Manuscript received April 23, 1993. This work was performed under the sponsorship of the U.S. Army Corps of Engineers and the Federal Railroad Administration through interagency agreements with the U.S. Department of Energy.

II. Dynamic Interactions of Maglev Vehicle/Guideway Systems

To simplify the vehicle model, only vertical motions of the vehicle are considered, based on the assumption that vertical motion is dominant and that other motions can be ignored when vertical motion is evaluated [1,3,8].

For a flexible guideway, elastic deformation must be considered. Attention is focused on vertical guideway deflection when analyzing vehicle/ guideway interactions. The classical Bernoulli-Euler beam equation is used to model guideway characteristics in virtually all recent analyses of vehicle/ guideway interactions.

A multicar, multiload vehicle traveling along a flexible guideway at a velocity v, as shown in Fig. 1, is considered in our mathematical model for dynamic analysis of vehicle/guideway interactions. The car body is rigid and has a uniform mass. The center of mass is consistent with that of moment of inertia. Each car is supported by certain numbers of magnets (or bogies) with linear springs and dampings, which form the primary and secondary suspensions of the vehicle.

Simulations on dynamics of a multicar vehicle are completed by using the model given in Fig. 1. Fig. 2 shows midspan beam deflections when multicar vehicles travel at 100 m/s. No matter how many cars are included in the vehicle, the maximum beam deflection remains the same. But the duration of deflections increases as car number increases. Fig. 3 shows the maximum displacements of the guideway midspan when the multicar vehicle travels at various speeds. Again, results for 1, 2, 3, and 4 cars are the same. As in previous studies on the concentrated-load single-car vehicle, maximum guideway displacements tend to increase as vehicle speed increases [1,2]. Fig. 4 shows a comparison of the Urban Tracked Air Cushion Vehicle (UTACV) ride comfort specification (ranging from 0-10 Hz) for multicar vehicles traveling at 100 m/s. Power spectral densities (PSDs) of multicar vehicle accelerations satisfy the ride comfort criterion.

III. Control Designs of Maglev Suspension

To achieve a quick response and a high-quality ride over a less-expensive guideway, control designs must be exploited in suspension systems. Moreover, with the assistance of suspension controls, a rougher guideway surface could be used and overall investment cost of the guideway could be reduced.

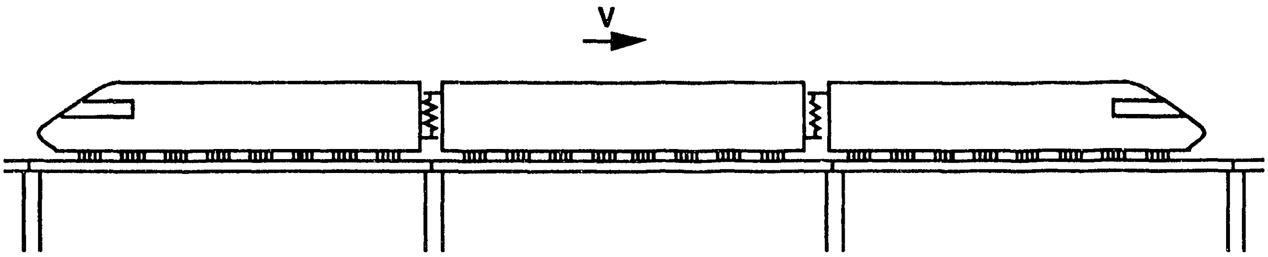

Fig. 1. Model of multicar, multiload maglev vehicle traveling along a guideway.

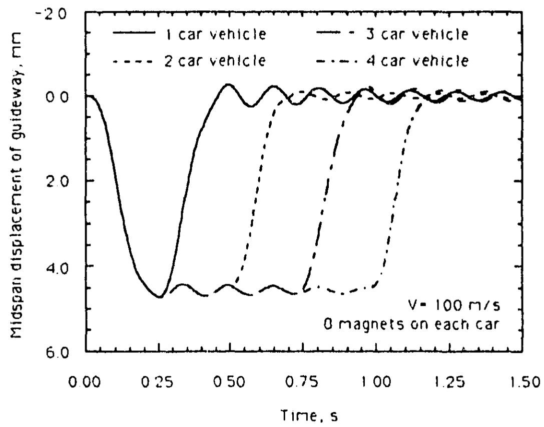

Fig. 2. Midspan displacements of guideway for multicar vehicles with eight magnets on each car traveling along the guideway at 100 m/s.

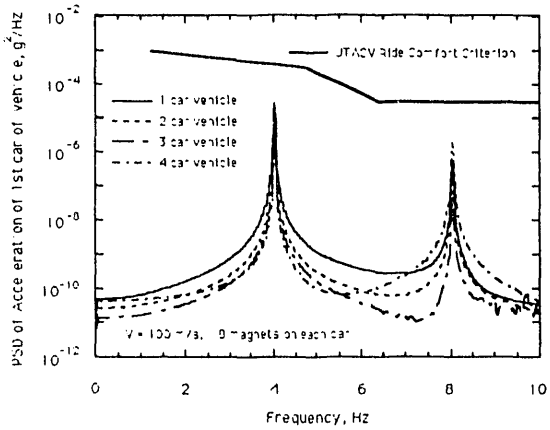

Fig. 4. PSD of car body accelerations when multicar vehicles with eight magnets on each car travel along the guideway at 100 m/s.

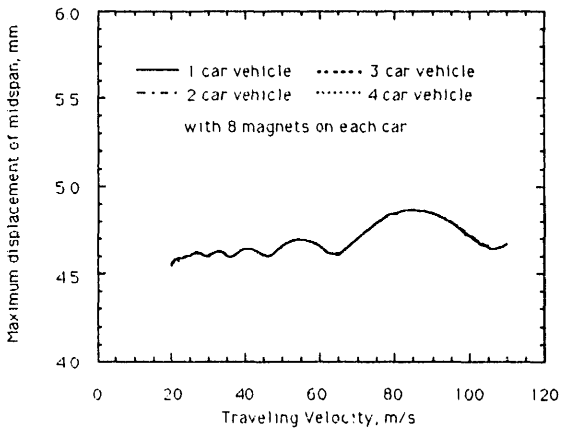

Fig. 3. Maximum midspan displacements of guideway when multicar vehicles with eight magnets on each car travel along the guideway at various speeds.

To investigate the improvement of the dynamic response and ride comfort of maglev systems, different control designs (active and semiactive) are examined in this study. For most control law synthesis, it is desirable to work with linear dynamic models of low order. A low-order maglev vehicle model, which may be selected as a two-degree-of-freedom quarter-vehicle model representing primary and secondary suspensions, is necessary in control design to formulate a low-order controller.

A one-dimensional vehicle model with two degrees of freedom (Fig. 5) and consisting of two lumped masses m_p and m_s, two linear springs k_p and k_s, and two viscous dampings c_p and c_s, representing primary and secondary suspensions, respectively, is used in the control synthesis of maglev systems. The passive parameters of the German Transrapid Maglev System TR06 are utilized for analysis in this study because no other Transrapid data are available in the literature [9-12].

An active primary suspension system is suitable for maglev vehicles. Such a system provides continuous or discrete variation in effective spring constants and damping coefficients, according to some control law that may be designed in software rather than hardware. In this approach, the force element can be realized with a linear electrohydraulic actuator that connects magnet and bogie in the primary suspension (see Fig. 6). A position sensor detects the air gap between magnet and guideway, and an accelerometer, mounted on the bogie, detects bogie motion. The resulting signals are processed by the controller according to designed control law in software, in turn causing the actuator to ensure that the air gap does not exceed specific tolerances within the safety margin and that the acceleration PSD of the suspension remains as low as possible in the specified frequency ranges in order to guarantee good ride comfort.

In this study, an active feedback control path is applied to the simplified vehicle model, which provides a less complicated control model. A lag-lead regulator is designed in the inner feedback path for the primary suspension (see Fig. 7).

It is noted that the active primary suspension system does not damp the excessive overshoots of secondary suspension in the transient response and the frequency response. To achieve the desirable values of the overshoots and the setting time, a semiactive control is introduced into the secondary suspension.

Semiactive suspension controls using an a "skyhook" damper (Fig. 8), offers a considerable advantage in terms of transmissibility control. It can be constructed, without the need for an inertial reference, using an active element under feedback control. It is straightforward to show that this can be done by a proportional control law involving the absolute velocity of the mass. It was proved that semiactive control with the skyhook configuration can increase the damping factor and that the resonant peak is suppressed while high-frequency transmission is reduced simultaneously [13].

Based on the principle of semiactive control of the secondary suspension, a feedback control path $k_s s$ (active damping) is added to the secondary suspension (see Fig. 7).

The PSD of vehicle acceleration with both primary and secondary feedback control is shown in Fig. 9. Ride comfort is much improved.

Figs. 10 and 11 show the comparison of transient responses of primary and secondary suspensions with unit-step input of guideway disturbance. Figs. 10 and 11 show that active and semi-active control designs indeed improve and response of vehicle and provide an acceptable ride comfort for maglev system.

The detailed parameters for Figs. 9 to 11 can be found in [3].

IV. Dynamic Stability of Maglev Systems

For safety, maglev systems should be stable. Magnetic forces are basically position-dependent, although some are

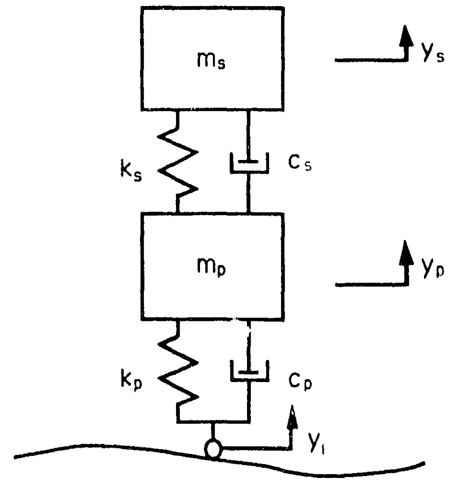

Fig. 5. One-dimensional two-degree-of-freedom vehicle model with primary and secondary suspensions for maglev systems.

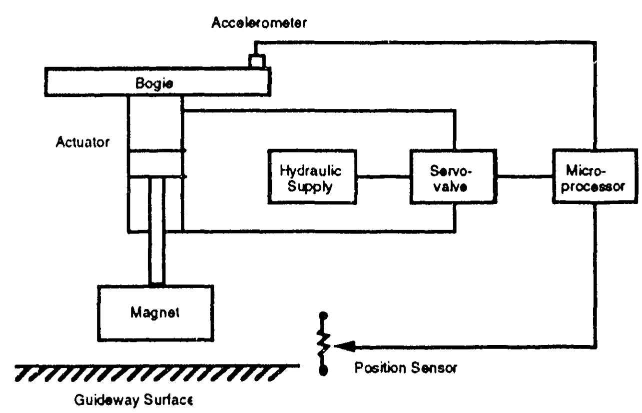

Fig. 6. Active electro-hydraulic system.

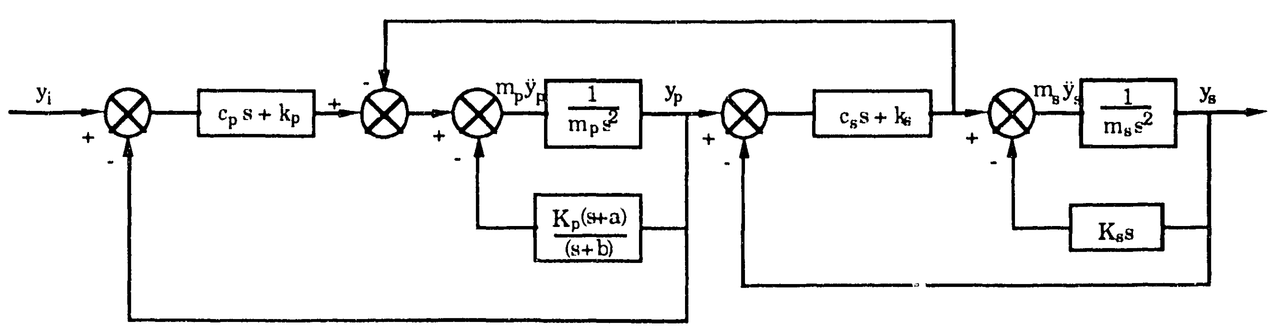

Fig. 7. Block diagram for two-degree-of-freedom vehicle model of maglev system with primary and secondary suspension feedback controls.

also velocity-dependent. These motion-dependent magnetic forces can induce various types of instability. In addition, the periodic structure of the motion-dependent magnetic forces may in some cases also induce parametric and combination resonances [5,6,14]. This study considers the stability of maglev systems and is based on experimental data, scoping calculations, and simple mathematical models. The objective is to provide some basic stability characteristics and to identify future research needs.

Different vehicles are considered [5], in order to provide an understanding of stability characteristics. Fig. 12 shows a cross section of a vehicle on a double L-shaped aluminum sheet guideway. Assume that the vehicle travels at a constant velocity along x direction. Two permanent magnets are attached to the bottom of vehicle and provide lift and guidance force F_{L_1}, F_{L_2}, F_{G_1}, and F_{G_2}. Assume at the initial state that $h_1 = h_2 = h_0$ and $g_1 = g_2 = g$.

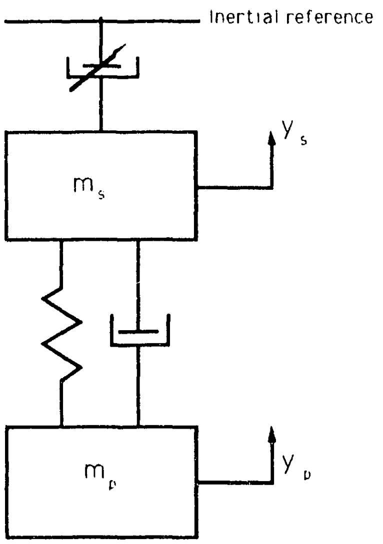

Fig. 8. Skyhook damper for secondary suspensions.

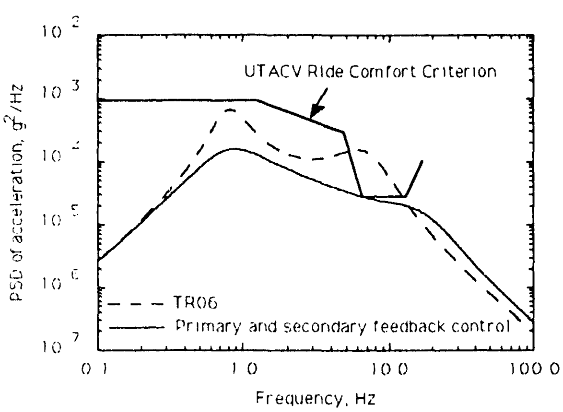

Fig. 9. PSD of vehicle acceleration using active and semiactive feedback controls in primary and secondary suspensions with vehicle speed V = 100 m/s and guideway roughness amplitude A = 10^{-6} m.

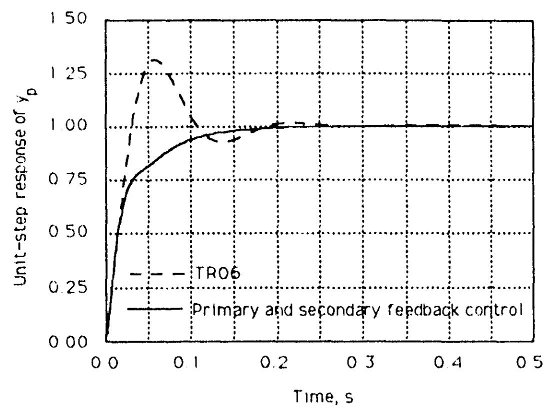

Fig. 10. Comparison of transient response y_p of primary suspension with unit-step input of guideway perturbation for TR06 and a new system using active and semiactive feedback controls in primary and secondary suspensions.

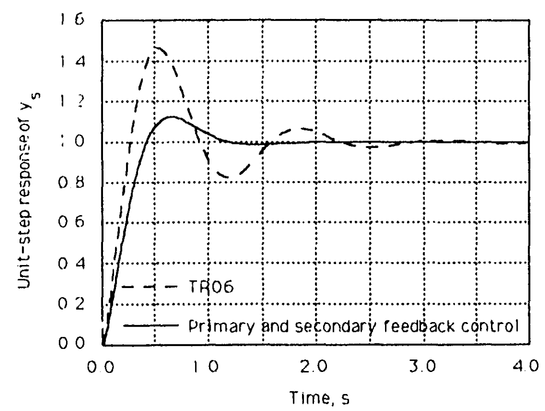

Fig. 11. Comparison of transient response y_p of secondary suspension with unit-step input of guideway perturbation for TR06 and a new system using active and semiactive feedback controls in primary and secondary suspensions.

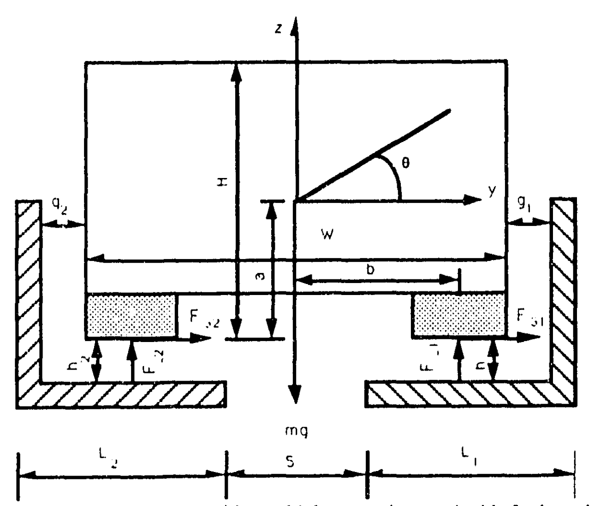

Fig. 12. Maglev system with a vehicle operating on double L-shaped aluminum sheet guideway.

With magnetic forces and stiffnesses measured by the experiments [5], the eigenvalues and eigenvectors of a maglev vehicle on a double L-shaped guideway were calculated with the theoretical model developed in this section. Some very interesting results were obtained from those calculations.

Fig. 13 shows that eigenvalues of vehicle motion versus levitation height vary when guidance gaps are fixed ($g_1 = g_2 = Y* = 12.7$ mm). The first mode ω_1 shows an uncoupled heave motion; its imaginary part of the eigenvalue is zero, while the second and third modes are coupled roll-sway motions. Within the range of height h = 19.0 to 35 mm, the imaginary parts of the eigenvalues appear not to be zero. This indicates that within this range, flutter does exist for these coupled roll-sway vibrations.

Figure 14 shows eigenvalues of vehicle motion versus lateral location of vehicle when $g_1 = g_2 = g_0 = 25$ mm and levitation heights h = 12.7 mm. We notice that for the third mode, which presents the transversal motion of vehicle, the real part is zero and imaginary part is not zero within a certain region. This indicates that the divergence is subjected to the lateral motion of the vehicle, given those vehicle and guideway parameters.

We must point out that the measured and calculated data for motion-dependent magnetic-forces and force coefficients are very limited and that damping effects were not considered in the above analysis. Even though divergence and flutter appear in the eigenvalue results, we still have difficulty in completely predicting the dynamic instability of this three-degree-of-freedom maglev vehicle model. Further research is needed in modeling to gain an understanding of dynamic instability in maglev systems.

V. Closing Remarks

(1) The dynamic interaction model of a maglev system with a multicar, multiload vehicle traveling along a flexible guideway was developed in this study. It was verified that this model is desirable for analyses of vehicle/guideway interactions in maglev systems.

(2) Active and semiactive feedback control designs in primary and secondary suspensions can be realized through electro-hydraulic systems. The conceptual designs of hydraulic controllers will be taken into account in our future work.

(3) Instabilities of maglev-system models have been observed at Argonne and other organizations. An integrated experimental/analytical study of stability characteristics is an important aspect of maglev research. Motion-dependent magnetic forces are the key 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. Efforts will be made to compile analytical results and experimental data for motion-dependent magnetic forces. When this work is completed, recommendations will be presented on research needs on magnetic forces. In addition, specific methods to obtain motion-dependent magnetic forces will be described in detail.

(4) Maglev may become a major transportation mode in the 21st century. Because the cost for a commercial maglev system is still very high, it is wise to consider dynamic control systems before completing the guideway design so that overall system cost can be reduced.

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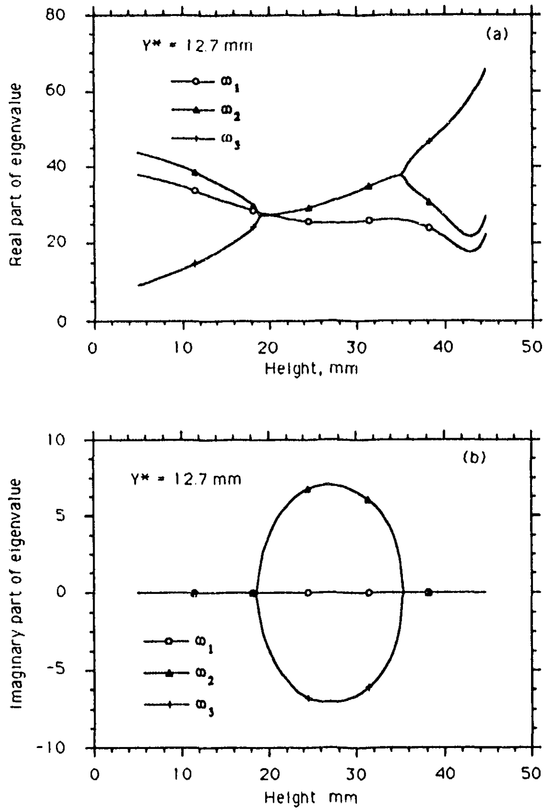

Figure 13. Maglev-system eigenvalues vs. vehicle levitation height, with Y* = 12.7 mm.

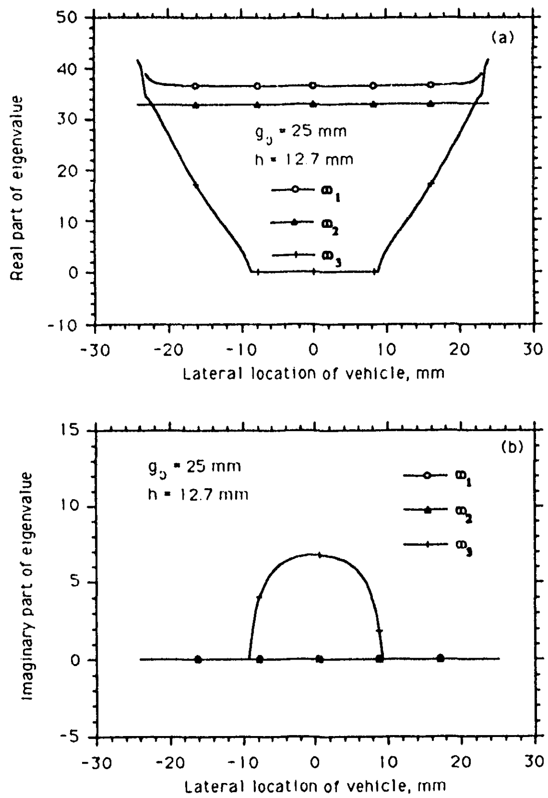

Figure 14. Maglev-system eigenvalues vs. lateral location of vehicle, with h= 12.7 mm and g_0 =25 mm.

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