Dynamic Simulation of the EMS Maglev Vehicle-Guideway-Controller Coupling System

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Abstract

Firstly, an integrated dynamic model of maglev vehicle-guideway-controller coupling system is established based on TR08 maglev vehicle and the elevated-guideway technology. Secondly, a special simulation program is developed. Finally, a sample simulation is carried out. Numerical results show that the dynamic model is appropriate and the simulation program is credible primarily. The studies in this paper can be used to evaluate and optimize dynamic performances of the high speed EMS maglev train system.

Keywords: maglev vehicle, guideway, feedback control, dynamics, numerical simulation

1 Introduction

Dynamic interactions among the maglev vehicle, the elevated-guideway and the levitation and guidance control system involving in the fields of mechanics, electronics, and civil engineering are so complicated that the theoretical study cannot be efficient to solve the dynamics problems. As a result, computer simulation is adopted because it can not only solve the complicated dynamic problems with smaller investment but also make the parametric study more convenient. Furthermore, numerical simulations are needed both to estimate the approximate dynamic behaviors of the early concept product and to evaluate and optimize system performances of the final design. As for the simulation on maglev system dynamics, first, the typical dynamic responses on the maglev test track can be calculated and analyzed to find the causes of the dynamic problems in practice and to put forward the improving measures; second, prediction and evaluation of dynamic responses of maglev transportation system can be done especially when the field test is impossible at present. Consequently, simulation studies can shorten the design cycle of maglev transportation system and save its costs.

With the development of maglev vehicle technology, studies on maglev vehicle-guideway dynamics are also advanced. Kortüm [1] and Cai [2] make a general review on the studies before 1990s, which reveal the basic laws of interaction between the maglev vehicle and the elevated- guideway and provide theoretical guidelines for the concept design of maglev transportation system. But there are two obvious disadvantages in the early studies: (1) the electromagnetic suspension is regarded as the constant force or the linear spring-damper, i.e. active interaction model between magnet and rail is not built. As a result, there is no coupling or partial coupling between the maglev vehicle and the guideway because the dynamic electromagnetic force is ignored. Of course, the influence of dynamic responses of the levitation and guidance control systems on maglev vehicle and guideway is also not considered; (2) the bogie is simplified as one and only mass module, which implies the studies on the lateral dynamics, especially curve negotiation behaviors of maglev vehicle is impossible. Nowadays, the German TR08 high- speed maglev vehicle, the Japanese HSST-100 low-speed maglev vehicle, the Chinese CMS-03 (developed by National University of Defense Technology) and CFC-01 (developed by Southwest Jiaotong University) low-speed maglev vehicle are ready for commercial application. Moreover, the first commercial high-speed maglev railway, Shanghai maglev railway adopted TR08 technology had been running since January 2004. So it’s the high time to establish the integrated maglev vehicle- guideway-controller dynamic model and then advance the simulation studies on maglev system dynamics.

Generally, there are two ways to simulate the dynamic behaviors of maglev vehicle-guideway-controller coupling system. (1) Based on the multibody system software such as ADAMS, SIMPACK and MEDYNA, etc., the FE-software like NASTRAN, MARC and ANSYS, etc., and MATLAB software, the mixed maglev vehicle- guideway-controller model can be built and co-simulation can be done. However, at present, a number of general simulation software cannot finish the simulation of such complicated coupling system independently and effectively. (2) More effective and applicable special simulation program of maglev vehicle- guideway-controller coupling system can be developed. According to the latter way, firstly, a dynamic model of maglev vehicle-guideway- controller system is established in the paper. Secondly, special simulation program is developed. Finally, a sample simulation is carried out and numerical results are analyzed.

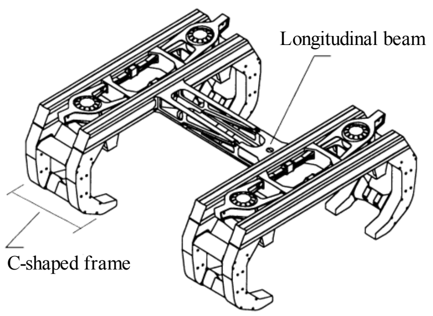

Fig.1 Bogie structure of TR08 vehicle

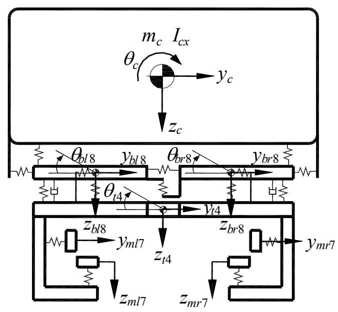

Fig.2 End view of TR08 vehicle model

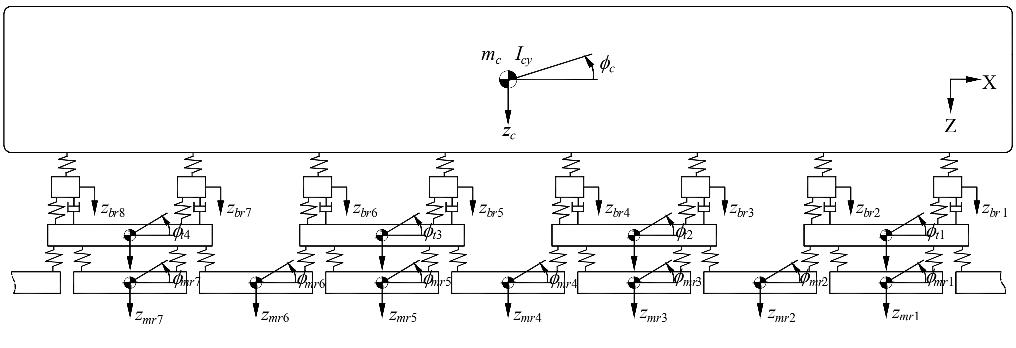

Fig.3 Elevation view of TR08 vehicle model

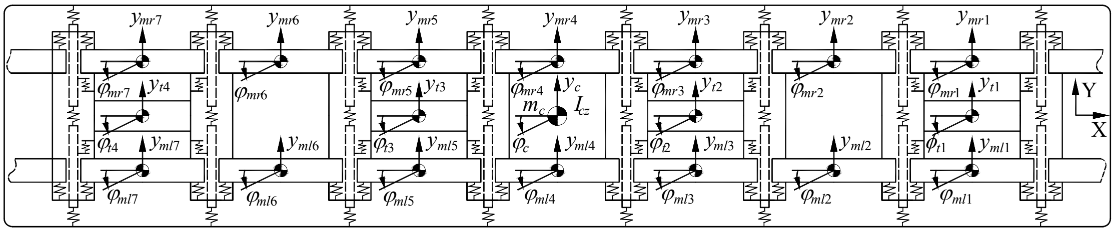

Fig.4 Plan view of TR08 vehicle model

2 Dynamic Model

2.1 Maglev Vehicle Model

Maglev vehicle structure can be divided into two parts: the upper car body and the lower bogie, the maglev car body is similar to that the conventional rail vehicle while the bogie is completely different from that of the rail vehicle. Hence, the bogie modeling is the key to maglev vehicle model.

There are special guidance magnets arranged on TR08 high-speed maglev vehicle, which adopts the design concept of magnet module and chaining structure. Fig.1 shows the sketch of the bogie of the TR08 vehicle [3, 4]. As is seen in Fig.1, there are two C-shaped frames for magnet arrangement and four pieces of detached bolsters. Regarding every component of TR08 vehicle as rigid body, a 133-DOF spatial model of maglev vehicle is established, as shown in Fig.2~4.

2.2 Elevated-guideway Model

Fig.5 demonstrates the cross section of thehigh-speed maglev guideway, which indicates that the functional components are fixed on the supported-beam. So the elevated-guideway can be modeled as Bernoulli-Euler (B-E) beam. Considering the 25m-length single span beam and the 50m-length two-span beam are used on German Emsland test track and Shanghai high speed maglev line [4, 5], the two kinds of guideway models are established respectively, which are described in literature [6].

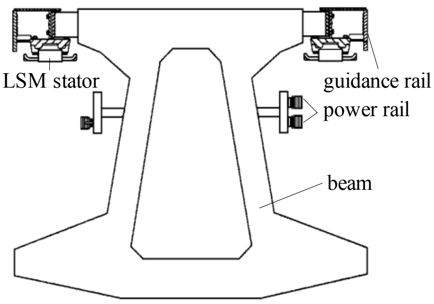

Fig.5 Cross section of maglev guideway

It is noted that B-E beam model is appropriate to solve one-dimensional oscillation of the elastic beam. When the vertical, lateral and twist oscillation of the elastic beam are considered, the finite element model should be more suitable than B-E beam model. But on condition that the oscillation is weak, it can be supposed that the vertical, lateral and twist motions of the beam are independent one another. Then, the three B-E beam models are developed to simulate three-dimension oscillation of the elastic beam, which can meet the requirements of engineering application.

2.3 Control System Model

Although various levitation and control strategies and methods have been put forward, the decentralized hierarchical control concept is widely adopted in practice. Based on the block diagram of the single magnet suspension system [7], as shown in Fig.6, the control system model is built by means of MATLAB Simulink toolbox. Then, the current control laws can be given as:

$$\Delta I = K_0\delta_d + K_1\dot{\delta} + K_2\ddot{\delta} \qquad \text{(Eq.1)}$$

where δ represents the airgap, δ_d the airgap change. And state space equations of the control system is described as

$$\begin{cases} \dot{\mathbf{X}}_c = \mathbf{A}\mathbf{X}_c + \mathbf{B}\mathbf{U} \\ \mathbf{Y}_c = \mathbf{C}\mathbf{X}_c \end{cases} \qquad \text{(Eq.2)}$$

where **A** is the system matrix, **B** the input matrix, **C** the output matrix, $\mathbf{X}_c$ and $\mathbf{Y}_c$ is the state vector and the output vector of the control system respectively.

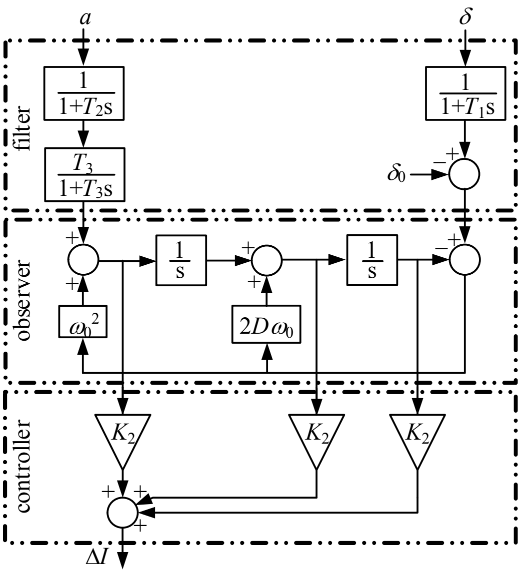

Fig.6 Block diagram of control system

3 Motion Equations and Solution

3.1 Motion Equations

Suppose that components of maglev vehicle are the rigid bodies, motion equations of the maglev vehicle are written as:

$$\mathbf{M}_v\ddot{\mathbf{X}}_v + \mathbf{C}_v\dot{\mathbf{X}}_v + \mathbf{K}_v\mathbf{X}_v = \mathbf{F}_m(\mathbf{X}_v,\ \mathbf{X}_c,\ \mathbf{Q}) \quad \text{(Eq.3)}$$

where magnetic force $f_m = \mu_0 S(Ni)^2/\delta^2/2$, $\mathbf{M}_v$, $\mathbf{K}_v$ and $\mathbf{C}_v$ represents mass matrix, stiffness matrix and damping matrix of the vehicle respectively, $\mathbf{X}_v$ and $\mathbf{X}_c$ the state vector of maglev vehicle system and control system respectively, $\mathbf{Q}$ the generalized displacement vector of the guideway, μ_0 the permeability of free space, i the current through the magnet windings, N the number of turns of the windings.

Using the modal analysis method, motion equations of the B-E beam can be express as

$$\ddot{q}_j + 2\xi_j\omega_j\dot{q}_j + \omega_j^2 q_j = f_j(\mathbf{X}_v,\ \mathbf{X}_c,\ \varphi_j) \quad \text{(Eq.4)}$$

where φ_j and q_j is the jth mode and modal amplitude, ω_j and ξ_j is jth modal circular frequency and damping ratio respectively. And the Q of Eq.3 equals to $(q_1, q_2, \ldots, q_n)$.

Consequently, motion equations of maglev vehicle-guideway-controller system can be derived from Eq.2~4, which is written as

$$\mathbf{M}(t,\ \mathbf{X})\dot{\mathbf{X}} = \mathbf{F}(t,\ \mathbf{X}) \quad \text{(Eq.5)}$$

where $\mathbf{M}$ is the time-varied matrix depended on the state vector $\mathbf{X}=[\mathbf{X}_v, \mathbf{X}_c, \mathbf{Q}]^T$, $\mathbf{F}$ is the nonlinear time-varied force vector.

3.2 Solution Methods

When electromagnetic force is simplified to a constant force or a linear spring-damper force, motion equations consist of Eq.3 and 4 are explicit ordinary different equations (ODEs). Then a vast number of numerical integration methods are availed, such as Runge-Kutta method and Newmark method *et al.* In addition, a new explicit integration method developed by Zhai [8] may be more efficient to solve the ODEs with a diagonal mass matrix.

Due to the nonlinear magnetic force and the acceleration term of Eq.1, motion equations consist of Eq.1, Eq.3 and Eq.4 are nonlinear ODEs, which is difficult to numerical integration. Therefore, some approximate techniques are needed to the engineering calculation. For instance, the acceleration term of Eq.1 can be ignored when the feedback coefficient K_2 is small enough, and then many classical numerical methods can be adopted.

The complete motion equations Eq.5 are implicit differential equations or differential algebraic equations (DAEs). Kortüm [9] points out that it is a difficult computational problem, and the modern projection techniques are in general preferable while the Baumgarte techniques usually introduce the additional "stiffness" to the problem.

4 Program Development

Based on the dynamic model of maglev vehicle- guideway-controller system, special simulation program is developed on the MATLAB software platform, whose flow chart is shown in Fig.7.

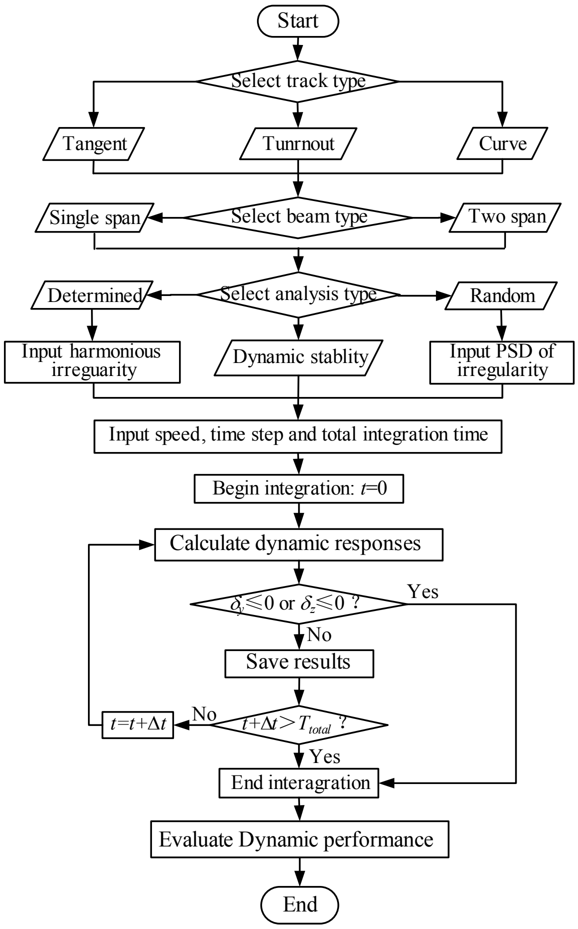

Fig.7 Flow chart of special simulation program

5 Sample Simulation

Because the TR08 vehicle data are rarely found in the literature, some parameters are estimate referring to the limited data from [3~5]. And the 50m-length two-span beam and the smooth guideway are considered in the following simulations. Basic parameters are as follows: the mass of the car body (loaded), truck, levitation magnet, levitation magnet and bolster is 3.9×10^4, 1320, 600, 400 and 80kg respectively, the stiffness and damping of the air spring is 0.4MN/m and 0.1MN·s/m, the nominal current and vertical airgap of levitation magnet is 20A and 10mm, the first order frequency of beam is 6.5Hz, K_0=6000, K_1=25, K_2=0.5, the running speed v=400km/h.

Fig.8 shows vertical displacements of the guideway, which indicates that the maximum concave displacement is 1.15mm and the maximum convex displacement is 2.54mm. So it can be concluded that the beam is so rigid in vertical direction that the acceleration of the car body is very small as shown in Fig.9. Fig.10 is the vertical airgap curve of the most frontal sensor of the maglev vehicle, which indicates that the maximum gap is 10.3mm. Fig.11 is the current curve of the most frontal magnet windings, which indicates that current fluctuation is less than 1.2A. In addition, as is shown both in Fig.10 and 11, the changes of air gap and the current are the greatest at the moment that the vehicle is entering the two-span beam. The phenomena accord with the fact that the change of the vertical displacements between the front and the back beams is discontinuous after the pier is regarded as rigid.

6 Summary

Based on TR08 high-speed maglev system, firstly, the maglev vehicle-guideway-controller coupling model is established, in which the vehicle model have 133 degrees of freedom, the guideway is modeled as the Bernoulli-Euler beam, and the dynamic model of the control system is introduced. Secondly, the special simulation program is designed and illustrated by numerical sample simulation. The results prove that maglev vehicle-guideway-controller coupling model presented in this paper is appropriate and the special simulation software is credible primarily, which can be used to evaluate the dynamic performances of the maglev vehicle and optimize system parameters in the future.

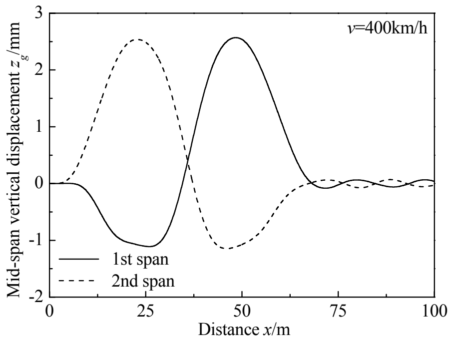

Fig.8 Midspan vertical displacement of guideway

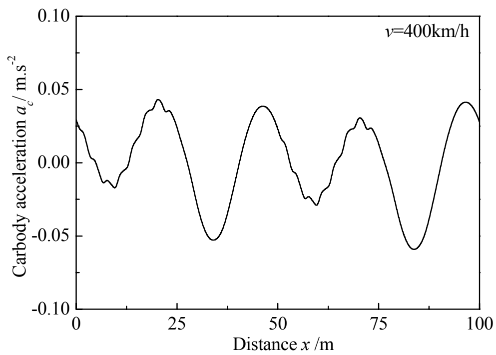

Fig.9 Acceleration of carbody

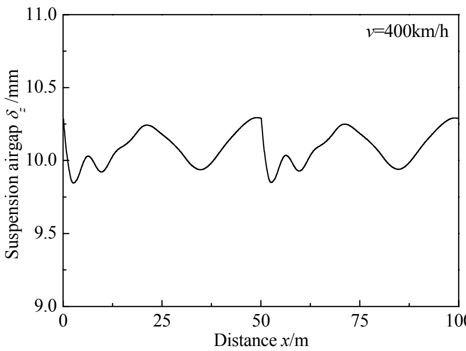

Fig.10 Levitation airgap on most frontal sensor

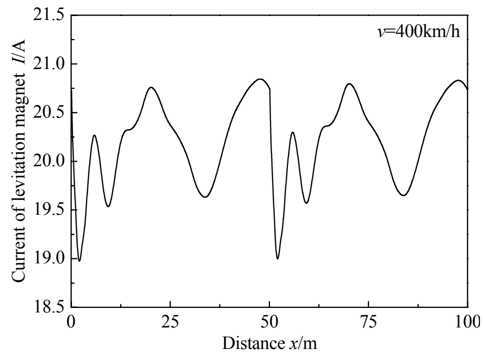

Fig.11 Current on most frontal windings

7 Acknowledgments

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