Review of Coupled Vibration Problems in EMS Maglev Vehicles

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The maglev train is a new type of guideway transportation for both long distance and urban applications in the 21st century. Recent progress in maglev technology indicates a probability of widespread commercial application of maglev systems in the near future. However, some economic and technical issues remain to be solved before the commercial application, and the vehicle-guideway coupled vibration problem is the most urgent technical problem that needs to be solved. In this article, the maglev vehicle-guideway coupled vibration problem, especially for the EMS system, is presented and divided into three main areas: the stationary vehicle-guideway, self-excited vibration; the moving vehicle-bridge coupled vibration; and the vehicle-guideway interaction caused by track irregularity. The available literature relevant to all the three coupled vibration problems is reviewed here, and the methodologies and main conclusions corresponding to each coupled vibration problem are compared and generalized as a reference for future work. The solutions proposed in the literature aiming to solve the coupled vibration problems are also enumerated, and their feasibility is discussed. Finally, work still required to solve the remaining problems is identified, and some suggestions for future research aimed at solving these remaining problems are provided.

1. INTRODUCTION

1.1. The Development of Maglev Systems

The maglev vehicle is a new type of guideway transportation for the 21st century. Compared with conventional railway systems, it has advantages of low noise, high speed, and the ability to climb steep slopes.[1] Research on maglev vehicles can be traced back to the 1960s.[1,3] The first-high speed commercial demonstration line around the world, 30 km long, was constructed in Shanghai, China, in 2003, using German Transrapid technology. The operating speed of this demonstration line is 430 km/h, and a maximum speed of 501 km/h has been achieved.[1] In Japan, a maximum manned-speed record of 581.7 km/h was achieved by the MLX01 maglev system in 2003;[2,4] in November 2004, a relative speed of 1026 km/h was reached when two vehicles were passing each other.[5] In 2005, the first low-speed commercial line, the Tubo-kyuryo Line (TKL), adopting HSST-100L technology, was established in Japan, demonstrating that the low-speed maglev system had reached the commercial application phase.[2,6,7] Countries such as Korea,[9–15] the United States,[16–23] and the United Kingdom[2,24,25] have also started their own maglev programs. Recently, it has been reported that Korea's Urban Maglev Program is planning to construct a 6.1 km urban maglev demonstration line at Incheon International Airport by 2011.[26] In China, a 1.5 km low-speed maglev test line was established in Tangshan in 2008; in 2009, the CMS04 vehicles began their test runs in this test line. In addition, the possibility of constructing a 170 km Shanghai-Hangzhou high-speed maglev line in China is also under discussion.[27] The progress in maglev technology indicates a high probability of widespread commercial application of maglev systems in the future.[2]

Generally, maglev systems can be divided into two categories: the EMS (Electromagnetic Levitation System) and the EDS (Electrodynamics Levitation System).[3] The EMS system uses electromagnetic attraction force as its suspending force, while the EDS system generally uses magnetic repulsive force. The German Transrapid system, the Japanese HSST system, the Chinese CMS system, and the Korean UTM system are EMS type, while the MLU system is a typical EDS system. The EDS system can also be divided into two subclasses: the PM (Permanent Magnet) type and the SCM (Superconducting Magnet) type. Compared with the EMS system, the EDS system enables a larger suspension gap (up to 100 mm) and is inherently stable; therefore, it is unnecessary to control the air gap between the vehicle and the track during the operation. However, the SCM type EDS system, such as the MLX system, needs sufficiently high speed to obtain enough induced current for levitation. Therefore, this system is suitable for long-distance and high-speed transport. The EMS system, although inherently unstable and requiring constant control, is able to levitate at a standstill and is commercially available.

Recently, during the development of the study on the EM-PM (Electromagnet-Permanent magnet) hybrid levitation system,[28,86] some researchers[3,28] have suggested that the EM-PM hybrid levitation system be independently categorized as a new maglev system. Compared with the EMS system, the power consumption of the EM-PM hybrid levitation system is remarkably lower since the permanent magnets in the EM-PM hybrid levitation system undertake most of the levitation load. Theoretically, the EM-PM hybrid levitation system can achieve "zero-power levitation" when properly designed. However, special issues of the EM-PM hybrid levitation system should be taken into account. For example, safety is of great concern when the levitation power breaks down during the operation because it is possible that the levitation magnets may lock up with the track because of the powerful attraction force generated by the permanent magnets. If this happens to a fast-moving vehicle, the result would be devastating.

Although the progress of maglev technology shows promise of its commercial application around the world, economic and technical issues such as the cost-effectiveness of the system, the reliability of the system, and the vehicle-guideway coupled vibration problem remain to be solved before its widespread application. Since the cost of the guideway is a high percentage of the total investment for a maglev system and the guideway plays an important role in the vehicle-guideway coupled vibration problem, this problem should be understood and settled. This study focuses on the coupled vibration problem in EMS maglev systems.

1.2. Description of Vehicle-Guideway Coupled Vibration Problems

It is well known that magnetic levitation alone is an inherently unstable system, and it needs active control to maintain stability. The interaction between the control force and a flexible or irregular guideway may cause the system to vibrate, which greatly affects its safety.

Some examples exist of problems caused by coupled vibration. In the early development period, the HSST-01, HSST-02, and HSST-04 experienced vibration that manifested as rapid variation of the gap between the levitating modules and the guideway because of insufficient guideway stiffness.[76] The TR04 system was found to be stably suspended on concrete beams but experienced high-level vibration when suspended on steel beams.[41,76] The American AMT vehicle performed well at the Edgewater test facility, but it experienced high vibration levels on the test line at Old Dominion University.[20,83] The TR08 in Shanghai vibrated when running on steel guideways in the maintenance depot or when crossing the turnoffs at a low velocity. However, the vehicle did not vibrate on the much heavier cement girders, which have a mass-per-unit length of 7 tons/m.[79,95] This indicates that the structure and the mass of the guideway are very important factors which greatly affect the dynamic response of the vehicle-guideway coupled system, and it indicates that the understanding of the relationships between the guideway parameters and the dynamic response is an important consideration in building a maglev guideway.

In general, maglev vehicle-guideway coupled vibration problems can be divided into three main categories:

(1) Moving vehicle-bridge coupled vibration: the elevated guideway is widely used in maglev systems. As with conventional rail transportation systems, the maglev system can also cause bridge vibration when the vehicles pass over it at a certain speed.

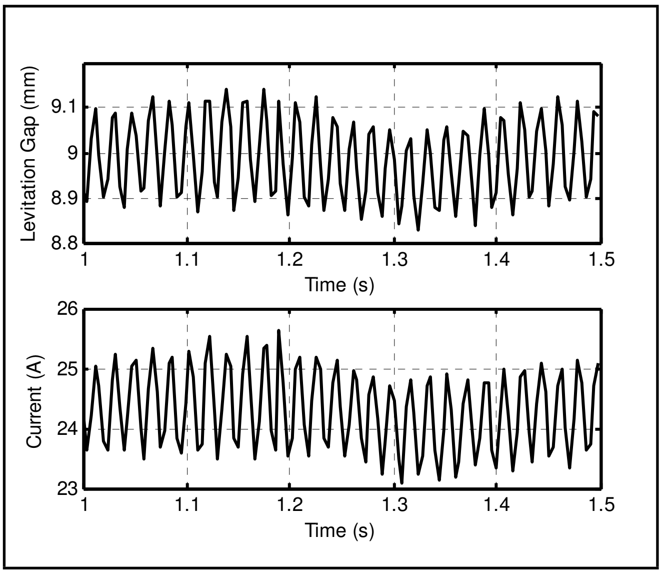

Figure 1. Recorded gap and current waveforms of electromagnet-track coupled resonance. The upper is the levitation gap of an electromagnet, and the lower is the current through the electromagnet.

(2) Stationary vehicle-guideway self-excited vibration: this occurs when the vehicle is suspended upon the guideway, standing still or moving at low speed, mainly due to the flexibility of the guideway. It is also named parametric resonance.[90] When this occurs, both the vehicle and the guideway begin to vibrate, mostly in the vertical direction. The stationary vehicle-guideway self-excited vibration can be divided into two subclasses: the stationary electromagnet-track coupled resonance and the stationary vehicle-bridge coupled resonance. The former generally happens between a single electromagnet and a segment of elastic steel track, and the frequency of the vibration is generally higher than 40 Hz, thus always making an annoying noise. The latter happens between one or more bogies and a bridge at a frequency below 20 Hz. Both of these two cases are unique phenomena that occur only in EMS and EM-PM hybrid maglev systems because the levitation gap is actively controlled in these systems and necessary conditions exist for the coupled resonance to occur when the vehicle is not moving.

Figure 1 shows a recorded waveform of the levitation gap and control current when the stationary electromagnet-track coupled resonance occurred, and Fig. 2 shows the waveform of the stationary vehicle-bridge coupled resonance when the vehicle passed over an elevated bridge at a very low speed. The waveforms shown in Fig. 1, Fig. 2, and Fig. 3 were recorded in the CMS03A low-speed maglev vehicle on the Tangshan maglev test line.

(3) Vehicle-guideway interaction as a result of track irregularity: the response of the maglev vehicle to track irregularity seems more complicated than the conventional wheel-rail system. Experiments show that periodic track irregularities may cause the bogies to vibrate intensely when the vehicle is running at a certain speed. Figure 3 shows an example of a waveform recorded as the CMS03A passed through a segment of periodically irregular track at a speed of 60 km/h.

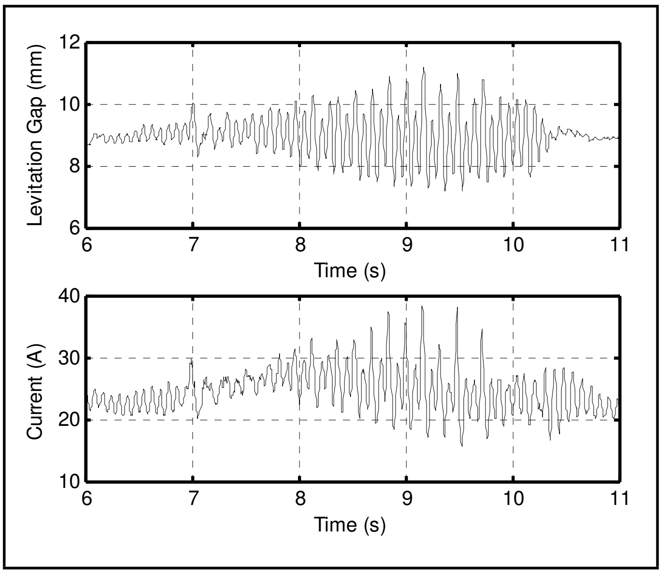

Figure 2. Recorded gap and current waveforms of vehicle-bridge coupled resonance when the vehicle was passing through an elevated bridge. The upper is the levitation gap of an electromagnet, and the lower is the current through the electromagnet.

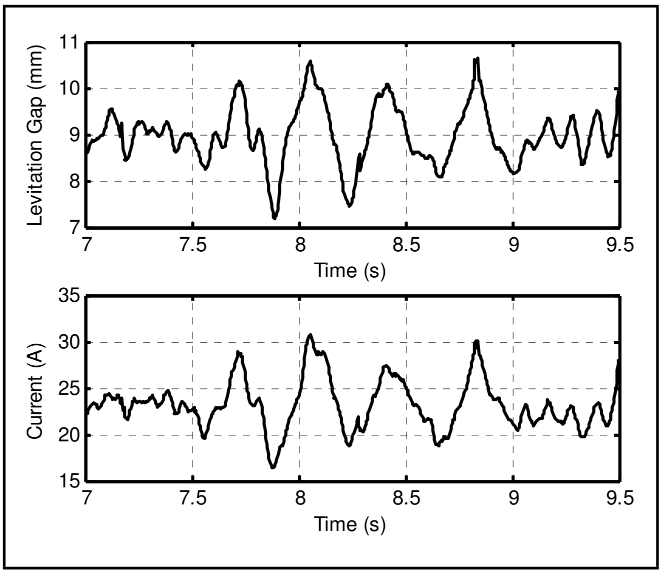

Figure 3. Waveform recorded when the CMS03A vehicle was passing through a segment of periodic irregular track.

2. CURRENT STUDY OF MAGLEV VEHICLE-GUIDEWAY COUPLED VIBRATION PROBLEMS

As mentioned above, vehicle-guideway interactions can be divided into three parts, and current research can be categorized in the same way.

2.1. Moving Vehicle-Bridge Coupled Vibration

2.1.1. Vehicle-bridge model

The vehicle-bridge model is of great importance in studying coupled vibration problems. In some research, the vehicle model is simplified as a moving force[31,33] or a moving mass.[30,58,60] However, these models are too simple to reflect the magnetic force. A developed 2-Degree-of-Freedom (2-DOF) model, which considers the secondary suspension system,[33,41,59,62,66] is shown in Fig. 4. For example, the maglev train has been modeled by Yau as a sequence of 2-DOF oscillators.[66] The primary suspension force F shown in Fig. 4 is simplified as a combination of a spring and a damper in some research.[33,41,68]

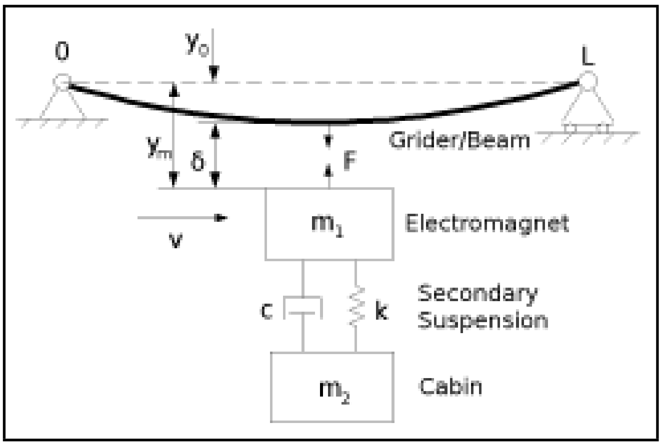

Figure 4. A simplified 2-DOF structure of single electromagnet-track coupled system.

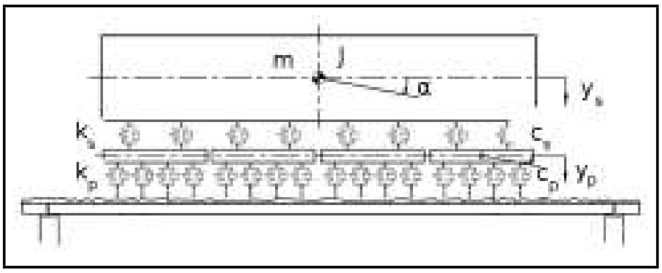

Figure 5. A vehicle model of TR06. The symbols k_p and c_p represent the equivalent stiffness and the damping of the primary suspension system.

Through simulation and comparison, Zhao et al.[39,40] and Cai and Chen[34] showed that the 2-DOF model will lead to a big error at high speeds, while each electromagnetic force being substituted by four springs and dampers can guarantee a precise simulation. Based on this work, more complex models have been established that more accurately represent the actual maglev vehicle configuration.[39–41,44,47,52,63] For example, Fig. 5 shows a model of the TR06 vehicle, which is widely used.[39–41,44,52] The suspension force in this model is substituted with a sequence of springs and dampers in order to simulate the distributed electromagnetic force. The symbols k_p and c_p in Fig. 5 represent the equivalent stiffness and damping of the primary suspension system, respectively.

The models listed above concern only the vertical movements of a vehicle. The lateral movements of the vehicle are also considered in some research.[36,48,61,100] Zheng et al.[61] established a 5-DOF vehicle model including four magnetic "wheels" and a car body, considering heave, sway, pitch, yaw, and roll motions. Zeng et al.[48] developed a full vehicle model of the low-speed vehicle CFC01, which included three bogies, six levitation modules, and a car body. The lateral movements of the suspension modules were also considered. Furthermore, a detailed 93-DOF model of the Shanghai maglev train has been developed by Shu et al.,[100,102] which consists of five separate sections. These models are effective in investigating the lateral interaction of the vehicle-bridge coupled system, and

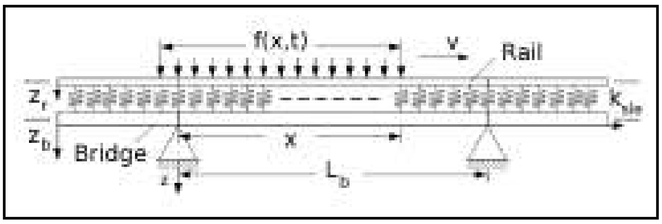

Figure 6. The double-deck model of the maglev guideway established by Wang et al.[82]

they are capable of evaluating the lateral ride comfort of the maglev vehicles.

The elastic guideway is generally described as a Bernoulli-Euler beam, because in most cases, the lengths of the maglev bridges are large compared to other dimensions, and the deflections of the bridges are small compared to their lengths.[30,31] Equation (1) is usually employed to describe the movements of the Bernoulli-Euler beam under excitations. Here, $y_k(x,t)$ is the displacement of the k^{th} beam, $F_k(x,t)$ is the primary suspending force along the k^{th} bridge, ρ is the mass-per-unit length of the beam, E is the Young's modulus of the beam, I is the area moment of inertia of the beam cross section, and c is the viscous damping of the beam:

$$EI\frac{\partial^4 y_k(x,t)}{\partial x^4}+\rho\frac{\partial^2 y_k(x,t)}{\partial t^2}+c\frac{\partial y_k(x,t)}{\partial t}=F_k(x,t) \quad (1)$$

Using modal analysis, the displacement of the beam can be expressed as

$$y_k(x,t)=\sum_{n=1}^{\infty} q_{kn}(t)\varphi_{kn}(x), \quad (2)$$

where $\varphi_{kn}(x)$ is the nth mode-shape function. Then, the partial differential Eq. (1) can be transformed into a set of ordinary differential equations, as follows:

$$\ddot{q}_{kn}+2\zeta_{kn}\omega_{kn}\dot{q}_{kn}+\omega^2 q_{kn}= =\frac{1}{Lm}\int_0^L F_k(x,t)\varphi_{kn}(x)dx. \quad (3)$$

Periodic simply supported single-span beams and continuous double-span or three-span beams have been analyzed in previous research.[30,31,34,58–60,63–66] Recently, a more precise rail-sleeper-bridge structure has been modeled by Wang et al.[82] As shown in Fig. 6, the actual guideway structure is modeled as a Bernoulli-Euler beam with evenly distributed springs supported on a simply supported beam structure. The resonance frequencies and modal shapes are deduced using theoretical analyses, which indicate that the stiffness of the support sleepers greatly influence the resonance frequencies of the guideway.

With the development of computer technology, vehicle-guideway models based on the finite element (FE) method and virtual prototype software have been produced.[9,10,19,23,71,72,75,77] The FE software is applicable in computing the frequency and bending shape of the maglev girders. For example, the frequencies of different maglev girders were computed by Lee et al., using the commercial structure analysis software ABAQUS.[29] Also, the maglev vehicle UTM-01 and the elevated guideway have been modeled as detailed 3D FE models by Han et al.,[9] using the commercial program LS-DYNA. The authors found that their simulation results agreed well with experimental measurements. The modeling and simulation of the UTM-01 using the multi-body dynamic analysis program DADS has also been reported.[10] Hong et al. employed the virtual prototype software ADAMS to develop a 3D virtual model of CMS03, and their simulation results and experiments agreed.[71,72,75] Shi et al. developed an elastic levitation chassis model and validated it using the FE software ANSYS.[77] The simulation indicated that the elastic chassis is likely to result in a parameter resonance in the presence of external excitations. FE models for the ODU test vehicle have also been established by Albert and Hanasoge,[19] and Deodhar et al.[23] Other research that involves the multi-body dynamic simulation software SIMPACK has been undertaken to determine the nature of the vehicle-guideway coupled dynamic model.[49,51] Recently, Hägele and Dignath separately calculated the equations of motion for the Transrapid high-speed maglev vehicle and the girders, using the software NEWEUL, and the models were then imported to MATLAB/SIMULINK to simulate the response of the vehicle/girder coupled system.[68] Generally, the models developed using FE software and Virtual Prototype software are precise enough to match with the actual system.

2.1.2. Analysis methods and main conclusions

The primary suspension forces of a maglev vehicle are evenly distributed and actively controlled. However, in some cases, the controllers are neglected in the analysis, and the vehicle is simplified as a moving force or a moving mass, or substituted by springs and dampers.[30,31,34,41,47,68] However, Teng et al. compared the dynamic responses of a moving load, a moving mass and active control, and showed that they are quite different.[65] Some researchers included the effect of the controller, but neglected the time delay of the current through the electromagnet.[52,66,67,70] However, this may lead to remarkable errors in the high-frequency range. Hong and Li[74] analyzed the model of a single electromagnet levitation system and found that the neglect of time delay in the current would result in the levitation system being equivalent to a spring-damper system. The dynamic characteristics of the controlled suspension system and the spring-damper system were also compared, and it was shown that the dynamic-response error increases significantly as the exciting frequency increases.

Research on control algorithms has also been undertaken. Proportional-derivative (PD) control and state-feedback control have been widely investigated, and force-control algorithms and flux feedback control have been successfully applied in practice.[23–25,49,51,53,58–62,64,65,80,81,83]The use of a Proportional-integral (PI) controller with its parameters adjusted by a BP Neural Network has been reported by Yau, who concludes that the Neuro-PI controller has the ability to change its control gains while the vehicle is moving at a high speed, and this satisfies the ride-comfort requirements.[66,67] However, the time delay between the input voltage and the output current on an electromagnet is neglected in Yau's work, which may lead to considerable inaccuracies in the control parameters. Optimal control methods have also been investigated by a number of authors.[30,37,63,100] Their research indicates that optimal control methods show advantages in searching for optimal or suboptimal control parameters that will satisfy desired performance requirements.

Some other levitation control algorithms have also been reported. For example, Wai and Lee discussed the application of the backstepping control algorithm in a 4-magnet EMS linear-motion mechanism.[56,57] Through simulations and experiments, it was found that the basic backstepping control (BSC) and improved adaptive backstepping control (ABSC) algorithm had explosion terms caused by repeated differentiations in the backstepping procedure, as well as chattering phenomena caused by the sign function. To overcome these problems, the authors proposed that an adaptive dynamic surface control (ADSC) algorithm, which was capable of online-observing the lumped uncertain vector, could effectively cope with these problems.[56] Furthermore, they designed a robust fuzzy-neural-network controller to alleviate the chattering.[57] However, the behaviors of the BCS and improved BCS algorithms in the moving vehicle-bridge coupled vibration problem need to be verified in the future.

When the deformation of the bridge is expressed as Eq. (2), and the modal analysis method is applied, the dynamical system can be translated into ordinary differential equations with periodic variable coefficients:[45,58,59]

$$\dot{X}(t) = A(t)X(t) + B(t), \text{ and}$$
$$A(t+T) = A,\ B(t+T) = B, \tag{4}$$

where T is a parameter associated with vehicle speed and span length of the beam. Floquet theory has been applied in the past to determine the stability of the ordinary differential equations with periodic variable coefficients.[54,55] However, this method requires a search of all eigenvalues of the basic solutions matrix, and for high order systems, this task is difficult. Zhou et al. defined the Lyapunov-characteristic numbers of Eq. (4), which allowed judgment of the system's stability. When the Lyapunov-characteristic numbers of the system are all less than zero, the dynamic system is stable; otherwise, it is unstable.[58] Compared with Floquet theory, this method has the merit of a relatively small computational effort.

For higher-order, complex dynamic models, it is difficult to judge the stability of the system theoretically, thus most of the researchers investigate their models through numerical simulations. To solve the ordinary differential equations, the Runge-Kutta method, Wilson-θ integral method, and Newmark's β method have been applied.[31,34,61,62,64–66,82] An explicit two-step time-integration algorithm based on the implicit Newmark's β method has been developed by Zhai, which shows great advantages in computation speed.[43]

Some commonly studied problems and conclusions can be listed here:

(1) *The effect of vehicle speed on the dynamic response of the coupled system.* It has been pointed out by some researchers that increasing the vehicle speed will increase the response of the bridge and the vehicle, although their models for demonstrating this are quite different.[13,34,63–65,83] For example, Dai investigated a 6-DOF single car and an 18-DOF three-car model on a continuous double-span beam, in which the controller was also taken into account.[63] The simulation concluded that the dynamic amplification factor increases practically linearly as the vehicle speed increases above 300 km/h, and that there is a local peak value at a speed of 250 km/h. A similar result was obtained by Zeng et al.,[47] which shows that the guideway response increases as the three-car vehicle speed increases, especially when the vehicle speed is above 200 km/h.

The span passage rate (span crossing frequency, passage frequency, or speed parameter) is defined as v/L, where v is the vehicle speed and L is the bridge-structure length.[31,63,66,82] It is believed that significant dynamic amplification will occur when the span passage rate equals the first-order vertical resonance frequency of the beam.[63,66] Zhao et al.[40] point out that 650 km/h is the worst speed for the TR06 to operate on the elevated beams in Emsland, because the crossing frequency equals half the first-order resonance frequency of the beam. Zheng et al.[61] indicate that the maximum displacement of the bridge increases before $v < v_c/2$ and decreases after $v > v_c/2$. Here, v_c is the first-order characteristic velocity of the vehicle, and it can be expressed as

$$v_c = \frac{\pi}{L}\sqrt{\frac{EI}{\rho}}, \tag{5}$$

where L is the span length, and EI and ρ are the bending rigidity and the mass density of the beam, respectively.

Similarly, when the span passage rate is close to the resonance frequency of the secondary suspension system, the response of the car body will be amplified. Wang and Nagurka[37] found that when the vehicle runs at 200 km/h, the vehicle crossing frequency is 2.61 Hz, which is close to the first resonance frequency of the car body (2.74 Hz): hence, a dynamic amplification is experienced in the car body. Zeng et al.[47] also found that the maximum vertical response of the car body occurs when the vehicle speed is 160 km/h for the three-car model running on a series of simply supported beams.

(2) *The structure and parameters of the bridge.* It has been pointed out that both the static and dynamic mid-span deflections of the beam decrease as the beam-stiffness increases, and that the dynamic amplification factors monotonically decrease as the beam stiffness increases.[63,65] Wang[83] concludes that the dynamic response of the guideway increases as the span length increases, and the response of guideway increases as its first-order resonance frequency decreases. Different guideways in the Emsland Transrapid test facility have been investigated by Zhao and Zhai,[39,41] and these investigations show that with the same vehicle speed, ground-mounted guideways perform better than elevated guideways, and double-span guideways perform better than simply supported guideways. However, double-span steel guideways are worse than concrete guideways, because they are not as stiff. Lee et al.[29] point out that the levitation-gap fluctuation of a vehicle running on a three-span continuous girder is smaller than on a double-span or a simply supported girder. However, they indicate that the span length of the girders have minor effects on the levitation gap and the dynamic amplification factor of the guideway. This conclusion seems to conflict with Wang's.[83] However, this is mainly because the guideway model in Lee et al.'s work is different

from Wang's: In Lee et al.'s work, the deflection ration (the ratio of span length and maximum static-deflection amplitude of the girder) is fixed at 1500, but it is not fixed in Wang's work.

(3) *The difference between the maglev system and the rail system.* The TR06 high-speed vehicle model (shown in Fig. 5) and a wheel/rail model based on the Japanese Shinkansen system have been established by Zhai and Zhao,[41,44] and different span lengths of bridges have been investigated. Comparison of these two high-speed systems showed that the ride comfort of the maglev train is much better than the wheel/rail system in extraordinary high-speed operation, and it showed that the dynamic response of the bridge will be smaller for the maglev system when the span length of the bridge is below 22 m. However, for the middle- and large-span bridges, the dynamic effect of the maglev train will be stronger than that of the wheel/rail train. Thus, small-span elevated bridges are recommended for the high-speed maglev system. A similar conclusion has been drawn by other researchers. For example, through the simulation of the UTM-01 maglev vehicle running on a series of 25 m single-span girders, Lee et al. pointed out that the dynamic magnification factor of the girder caused by the maglev vehicle was generally not severe compared with that caused by a traditional railway vehicle.[29]

2.2. Stationary Vehicle-Guideway Self-Excited Vibration

Generally, the vehicle-guideway models used here are simple, partly because of the complexity of the analysis, and partly because there is no need to establish a complex model. The models used here are mostly based on the single electromagnet-beam coupled model. The model shown in Fig. 4 is widely used, in which the support beam is generally considered as a simply supported Bernoulli-Euler beam. PD control and state-feedback control are generally used in this problem because they are not only simple but also robust.[18–20,69,76–79,84,86]

Early research was primarily focused on linear models, and linear control theory was usually applied to investigate the stability of the coupled system. Xie et al.[70] established a track-sleeper-roadbed model and deduced the dynamic equations of the guideway using the FE method. A single electromagnet levitation system was adopted to analyze the principle underlying the coupled vibration problem. Through the analysis of the characteristic equation, a necessary and sufficient criterion to ensure stability of the coupled system was derived. It was found that the deflection of the elastic guideway is the key factor causing resonance instability, and that increasing the damping of the guideway or decreasing the mass ratio of the vehicle and the guideway could increase the stability of the coupled system. Deng et al.[50] built a single magnetic-beam-controller model using SIMPACK software. Through the analysis of the eigenvalues of the system, they concluded that if the first-order resonance frequency of the beam approaches the natural frequency of the control system, the coupled system will become unstable. They also showed that increasing the damping ratio of the beam was beneficial to the stability of the coupled system.

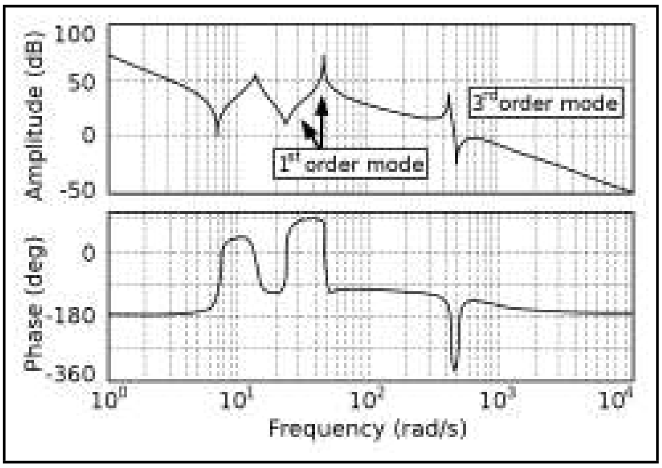

Figure 7. Bode plot developed by Hong et al.[73,76]

Zhao[41] derived a nonlinear coupled electromagnet-guideway-controller model, adopting the model shown in Fig. 4, with the Runge-Kutta method being applied to solve the differential equations. Through numerical simulation, it is concluded that the resonance instability is mostly caused by inappropriate resonance frequency relationships between various parts of the system. When any two or three of the following frequencies — the natural frequency of the controller, the first-order resonance frequency of the support beam, and the secondary suspension frequency of the vehicle — get too close to each other, the vehicle-guideway resonance tends to occur.

Analyses carried out in the frequency domain have been undertaken by Hong et al.,[73,76] who investigated a model of a single electromagnet suspension system on a flexible beam. Through linearization, they derived a linear coupled dynamic model. Based on Nyquist stability theory, the open-loop Bode plot (shown in Fig. 7) of the system was analyzed, and a sufficient condition to ensure stability was derived. It was found that the first-order vibration mode of the beam does not lead to resonance instability of the coupled system because the phase-frequency curve shown in Fig. 7 never crosses the -180 line; however, the third-order mode of the beam may lead to resonance instability since its phase-frequency curve crosses the -180 line. However, in practice it has been found that the first-order vibration mode of the beam can also lead to coupled resonance instability. This is mostly because the configuration of the model in Hong's work is somewhat different from a real maglev vehicle-guideway coupled system. Nevertheless, this method in the frequency domain offers a new approach for analyzing the vehicle-guideway coupled system. For example, the frequency responses of the levitation system under different conditions were investigated by Zhou and Li[88] in the analysis of the low-frequency vibration of EMS maglev bogies, when the vehicle is at a standstill.

Recently, analyses of the nonlinear coupled model have been undertaken by Shi et al.[78] and She et al.,[79] who analyzed the Hopf bifurcation of the vehicle-guideway coupled system and found the stable frequency range of the guideway. The main conclusions follow: 1) as the vehicle load is increased, the lowest-order resonance frequency of the bridge should be increased to avoid resonance; 2) higher bridge resonance frequencies require a higher natural frequency of the controller;

and 3) the larger the stiffness of the secondary suspension system, the narrower the stable frequency range of the guideway. It is also pointed out that if the frequencies of the subsystems get close to each other, resonance tends to occur.

Furthermore, based on a nonlinear single electromagnet suspension model, Wang et al.[80–83] theoretically investigated the effect of time delay in the feedback paths, including time delay in the gap signal, the velocity signal, and the acceleration signal, on the stability of the coupled system. The results show that the time delay plays an important role in the vehicle-guideway coupled resonance problem; insufficient stiffness of sleepers and tracks is the key factor that causes the vehicle-track resonance instability, but decreasing the stiffness of the bridge seems not to affect the onset of the vehicle-bridge resonance condition. It was also found that an appropriate time delay can be applied in the control algorithm to suppress the vehicle-track coupled resonance when the stiffness of the tracks and sleepers is reasonable. Some experiments have been carried out on a maglev bogie, which proved that the analyses are correct.

While most of the research on the stationary vehicle-guideway self-excited vibration problem is based on theoretical analysis, some researchers analyze this problem though experiments and measurements. Lee et al.[91] measured the free vibration of the guideway, the vibration of guideway, and levitation gap when the vehicle was still as well as when the vehicle was running. Through analysis of the measured data, the natural frequencies and the damping ratios of three kind of steel girds were estimated using FFT transformation and Hilbert transformation, and it was found that the stability of the coupled system was better on the girders that had lower fundamental resonance frequencies. This conclusion may be consistent with the conclusions of the researchers listed above, since lower fundamental resonance frequency of the girder will get farther from the natural frequency of the levitation control system.[41,50,78,79]

To overcome the stationary vehicle-guideway self-excited vibration problem, a number of solutions have been proposed, including increasing the damping of the guideway, reducing control parameters, and increasing suspension gaps.[76,83] The method of adjusting the resonance frequencies of the guideway and the controller has been discussed by Han et al.[12] and Zhao.[41] For example, through the analysis of a 3-DOF model in the frequency domain, Han et al.[12] pointed out that the lower the natural frequency of a guideway, the lower the deviation of the air gap. Therefore, in order to reduce the air gap deviation, the natural frequency of the guideway should be decreased. However, these solutions are either too difficult to realize or too costly.

Li et al.[84] analyzed the single electromagnet levitation model and pointed out that the differential of the gap signal used in the feedback path is beneficial for eliminating the resonance. A robust state observer was designed to obtain the differential of the gap signal. Simulation and experiments indicate that this method is effective in eliminating the resonance vibration. Cheng et al.[86] investigated the linearized model of the EM-PM hybrid levitation system and concluded that the stationary vehicle-guideway self-excited vibration could not be suppressed when the damping of the controller was obtained from the integral of the accelerometer, and that the differential of gap signal could significantly suppress the self-excited vibration. In addition, Li et al.[85] proposed an adaptive controller based on oscillation observation and phase-lead compensators. A general Kalman filter was applied to estimate the frequency of the oscillation from the gap signal, and then the parameters of the phase-lead compensators were adjusted according to the estimated frequency. The simulation showed that this method is also feasible. Zou et al.[87] designed a levitation controller based on the feedback linearization method and indicated that the proposed controller behaved better than the conventional PID controller when the flexibility of the guideway was taken into account.

Zhou et al.[89] proposed an adaptive vibration control algorithm based on a virtual damper. A nonlinear oscillation observer and an adjustable virtual damper were designed separately. The simulation and the experiments carried out in CMS03A showed that this algorithm is effective in suppressing the low-frequency oscillation of the bogies.

Yabuno et al.[90] proposed an active-control strategy for the stabilization of parametric resonance in a maglev body. They applied a pendulum-type vibration absorber, which was designed to directly cancel part of the force activating the resonance. A phase-locked-loop (PLL) was applied to track the disturbance frequency and to generate the phase-locked input fed to the absorber. Experiments were undertaken on a magnetic suspension setup, which showed that the parametric resonance was globally cancelled by the absorber.

Recently, a passivity-based levitation controller design approach was studied by Shimizu et al,[92,93] which was reported to be effective in suppressing the elastic vibrations of a flexible beam. The model in their research consists of two fixed electromagnets and a flexible beam suspended beneath the electromagnets. In their design approach, the whole system is decomposed into the electrical subsystem and the mechanical subsystem, and controllers for each subsystem are designed separately to ensure the controlled subsystems are both passive. The most significant advantage of this design approach is that the process does not need any model reduction, and the designed nonlinear controller can ensure suppression of all modes of elastic vibrations. Simulations in their work have shown that the designed controller can ensure the stability of the coupled system in the sense of Lyapunov. Similar work has also been done by Namerikawa and Kawano.[94] In their work, experiments on an iron ball suspension system showed that the passivity-based controller achieves better performance than the conventional PID controller. However, this design approach has a relatively high requirement of model parameters, such as the mass of the levitated body. In addition, the designed controller needs the derivative of the levitation gap, which always contains intense noise in a real maglev vehicle.

Although the work listed above has been comprehensive in investigating the principle of the stationary vehicle-guideway self-excited vibration problem and in developing a solution to overcome the problem, a substantial amount of work is still needed in this area, especially in the area of vibration-suppression algorithms that can be used in a full-scale maglev vehicle.

2.3. Vehicle-Guideway Interaction as a Result of Track Irregularity

Generally, the guideway vertical random irregularity is expressed as a PSD (Power Spectral Density) function. Due to the lack of experimental data for maglev guideways, most research adopts PSD functions that have been determined for railway tracks or highways. The PSD function in Eq. (6), which is derived from field data for highways, airport runways, and railway tracks, has been widely adopted.[35,37,41,99] Here, A is a roughness spectral parameter, Ω is the roughness wave number (in rad/m), and n is the frequency exponent, which varies from 1.5 to 2.5:[39,41]

$$S(\Omega) = \frac{A}{\Omega^n}. \tag{6}$$

It should be mentioned that Eq. (6) is an expression of the PSD in the spatial domain, and Ω is in rad/m. For the PSD in the frequency domain, the expression should be modified as[35]

$$S(\omega) = \frac{Av}{\omega^n}. \tag{7}$$

In Eq. (7), v is the vehicle speed and ω is the angular frequency of the irregularity, which is in rad/s. Equations (6) and (7) are applicable for speeds below 300 km/h. However, they need modification to account for the long wavelength irregularities when the speed exceeds 300 km/h. A modified spatial PSD function of track irregularity, which is also applicable for high speeds, is expressed by Eq. (8).[41,42] Here, C is a constant related to the controlled wavelength of track irregularity:

$$S(\Omega) = \frac{A}{\Omega^n + C}. \tag{8}$$

Other PSD functions, like the American track spectrum function, have also been introduced.[8,31,66] For example, a PSD function in the frequency domain based on experiences with traditional railway tracks, with a modification according to experience at the Oe maglev test site, has been proposed by Morita et al.[8] and is represented by Eq. (9):

$$S(\omega) = \frac{Av}{\omega^n}\frac{(\Phi_1 v)^2}{\omega^2 + (\Phi_1 v)^2}, \tag{9}$$

where v is the vehicle speed, and Φ_1 is the cut-off spatial frequency of the guideway irregularity (in rad/m). A is determined by the maintenance practice and data of the Oe maglev test tracks. It has been shown that the calculation accurately simulates the characteristics of the maglev vehicle Linimo on the Oe test track. A similar PSD function with improved band coefficients has also been adopted by Yau.[67]

A random irregularity model proposed by Tsunashima and Abe[96] has been adopted by Kwon et al.[13] and Zhao and Zhai,[39] which shows that all track irregularities can be divided into three subsections according to their wavelength: less than 3 m, 3-60 m, and above 60 m, as shown in Fig. 8.[39]

For a linear system, the PSD response of the vehicle can be obtained by[7,8,35,99]

$$\Phi_x(\omega) = |T(j\omega)|^2 S(\omega), \tag{10}$$

where $T(j\omega)$ is the transfer function of the dynamic system and $S(\omega)$ is the PSD of guideway irregularity in the frequency domain.

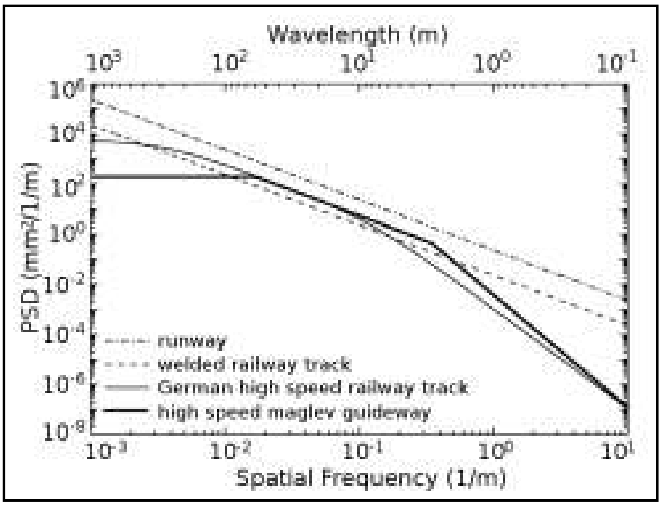

Figure 8. PSD model adopted by Zhao et al.[39]

However, for complex and nonlinear models, numerical simulation is generally adopted, which requires the production of the guideway profile. In most cases, the guideway profiles used in the simulation are produced on the basis of the specified PSD function. The commonly used methods to generate a spatial irregular profile include the trigonometric series approach, the inverse fast Fourier transform (IFFT) method, and the white noise filtration method.[8,13,46,63]

An algorithm constructed based on the PSD equivalency in the frequency domain has been proposed by Chen and Zhai.[46] In their approach, the magnitude of the frequency spectrum of the track profile is obtained according to the given PSD function, and the phase spectrum is generated using a random function, then the track profile in the time domain is derived using the inverse Fourier transformation. Simulation shows that this algorithm is better than the trigonometric series approach, and it has been adopted by Zhao et al.[39,41]

In some cases, determinate track disturbances are also introduced to assess the character of the controller. For example, step and sine wave disturbance of the track have been applied to investigate the vehicle response.[10,15,49,100–103] A section of measured railway track irregularities with a magnitude reduction of 1/4 has been used by Shu et al., and the periodic deformation of the guideway was assumed to have an amplitude of 2 mm and a spatial variation in the form of a sine wave.[100,102] A combination of track-surface roughness, span geometrical errors, and the deformation of the span has also been introduced.[37,38] These determinate disturbances are useful in investigating the performance of the control algorithm. For example, the response of the vehicle to the step disturbance of the guideway helps the designer determine the parameters of the controller, and the response of the levitation gap to a specified tonal disturbance frequency reflects the bandwidth of the levitation system as well as the tracking performance of the controller.

In addition, the influence of land subsidence along a guideway route on the response of a moving maglev vehicle has also been studied by Yau.[67] A concave-type settlement profile with a maximum settlement of 0.1 m and a maximum length of 300 m was taken into account in Yau's model. Through numerical simulation, it was found that the vehicle with the smaller levitation gap would be significantly affected by the ground settlement, and that increasing the levitation gap would decrease the influence of the ground settlement.

Recently, some researchers also used the measured roughness of the maglev guideway for their simulation. For example, Lee et al.[29] used the irregularity of the reaction plates measured at the test track in the Korean Institute of Machinery and Materials in their study. The profiles were measured every 1.25 m along the test track, and the maximum irregularity ranged around ± 4.1 mm. The simulation using the measured track-roughness is more reliable than using the profiles produced by a specified PSD function.

The ride comfort is mostly a concern when investigating the vehicle response under guideway irregularities. The ride comfort is generally measured by UTACV (the Urban Tracked Air Cushion Vehicle) ride comfort criterion, the ISO 2631 ride-quality criteria, and the Sperling ride index.[23,32,34,35,37,39,41,53] The UTACV criterion was proposed by the US Department of Transportation for AGT (Advanced Ground Transportation) for high-speed vehicles in 1971, and it is widely used to evaluate the dynamic behavior of maglev vehicles.[23] The UTACV criterion is shown in Fig. 9. In addition, the UTACV criterion requires that the vertical acceleration of the vehicle be below 0.05 g.

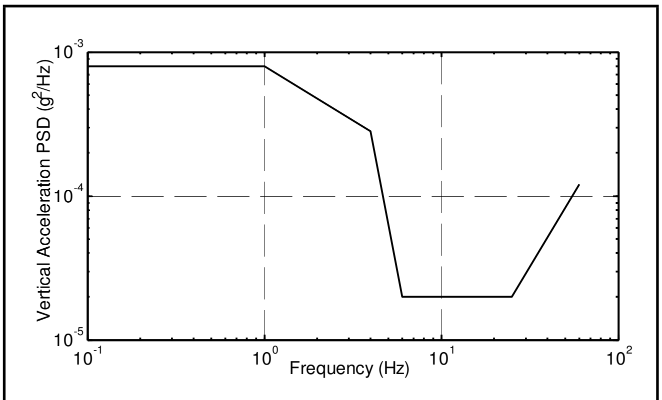

Figure 9. The UTACV ride-comfort criterion in the vertical direction.

The vehicle models and control algorithms used in this research are mostly the same as those used in the moving vehicle-bridge coupled vibration problems. For example, the levitation control system has also been simplified as a spring and damper system in some research.[32,35] PD and state-feedback control are also widely used.[7,8,23,49,53,97,99] A kind of preview control is proposed by Wang and Nagurka, which reveals that the preview of the track irregularity as an input to the control system may reduce the gap error and reduce energy consumption.[37] In addition, slide-mode control, neural network control, optimal control, and a genetic algorithm, have also been used in studies of the vehicle-guideway interaction problem when considering the track irregularities.[15,66,67,100,103] Generally, the slide-mode control has excellent tracking performance and, thus, the levitation gap fluctuation is smaller than the conventional PID controller; however, the chattering phenomenon due to the sign function is undesirable, and it may excite high-frequency parameter resonance. The neural network control has the advantage of searching for a set of optimal control parameters so that the vehicle can reach the minimum vertical acceleration response under the excitation of guideway irregularities. However, the neural network needs off-line training before it is put into operation, and thus, a training database is required. Preparing the training database is always time-consuming. For example, in Yau's work, 2040 data patterns, which were generated by extensive simulations, were used to train the BPN.[66] The genetic algorithm is also good at generating a set of optimal control and structural parameters, such as the stiffness and the damping of the secondary suspension system, but it also needs an evaluation function, which greatly depends on the experience of the designer. In addition, the evaluation is time-consuming, so in some cases, the searching process is carried out off-line.[103] Generally, these control algorithms only appear in the literature for theoretical analyses, and the algorithms used in a full-scale maglev vehicle have not been reported yet. For example, the LQG (Liner Quadratic Gaussian) controller was applied by Lee et al.,[29] in the investigation of vehicle response under excitation of guideway irregularities. However, the authors noted that the LQG controller was not an actual control algorithm for the UTM-01 vehicle, and it was used only for comparative study.

Some main conclusions can be listed here:

(1) The vibration of the vehicle and the dynamic-amplification factor increase as the guideway surface roughness increases.[63,67]

(2) The flexibility of the guideway and the periodic piers has a significant affect on the vehicle's ride comfort. For example, three different types of guideways at the Emsland Transrapid test facility have been investigated separately by Zhao and Zhai, and the results show that the vehicle ride quality meets the UTACV criterion, except the double-span steel elevated guideway at 400 km/h, in which a 2.2 Hz peak exceeded the UTACV criterion as a result of the periodic excitation of the guideway.[39,41] In Lee et al.'s work, it was found that the suspension gap fluctuated more severely when the bogie crossed from one span to another, because of the sharp slope and abrupt change of the guideway deflection at the support.[29] It was also found that the suspension-gap fluctuation was dominated by the irregularity of the track at speeds less than 60 km/h, yet it was dominated by the deflection of the girders at higher speeds. Others have found similar results.[13,32,35,41,49]

(3) The chosen control algorithms and control parameters have a large influence on ride comfort. For example, Yau[66] proposed a trained neuro-PI control algorithm, and the simulation shows that this controller has the ability to control the acceleration amplitude of the vehicle within an allowable range. Yau also indicated that the dynamic response of the vehicle with a larger levitation gap might be larger than a vehicle with a smaller one under the same guideway conditions.[67] Kusagawa et al.[103] proposed a GA algorithm that can provide a wide search of control parameters and find their optimum or semi-optimum values, thus providing the best ride quality.

Some measures can be taken to improve ride comfort. First, as the examples listed above, the control algorithms and the control parameters can be optimized to minimize the dynamic amplifier of the primary suspension system in the presence of guideway irregularities. Second, the decrease of the guideway surface roughness will definitely improve the ride comfort; however, this will increase the project's cost. Third, parameter optimization and active control of the secondary suspension system can also improve ride comfort. For example, Watanabe et al. and Hoshino et al. proposed a combined control of the primary and secondary suspensions of the superconducting maglev vehicle.[104,105] In their research, the secondary suspension system between the car bodies and the bogies was semi-actively controlled using a variable damper, and the skyhook control laws were applied. To reduce the high-frequency vibration of the primary suspension system, power collection coils were used as a power generator system, to generate damping force to the primary suspension. Simulation of the car body frequency response showed that the combined control system could significantly reduce lateral and vertical vibrations of the vehicle, and thus, could considerably improve ride comfort. The semi-active control of the secondary suspension system has also been applied in railway vehicles.[106] Although this research is based on the superconducting EDS maglev vehicle and conventional railway vehicle, the idea of active control of both the primary and secondary suspension systems should also be applicable to the EMS maglev system. Moreover, Zheng et al.[107] proposed an active control method for a railway vehicle that included consideration of the car body flexibility. A controllable dynamic vibration absorber was mounted under the car body to decrease the vibration of the car body. This method could be used in maglev vehicles to enhance ride comfort.

3. SUGGESTIONS FOR FUTURE WORK ON COUPLED VIBRATION PROBLEMS IN MAGLEV VEHICLES

A considerable amount of research has already been undertaken on maglev vehicle-guideway coupled vibration problems, as discussed in the previous section. However, effort is still required to fully understand the principle underlying the vehicle-guideway interaction and to develop practical solutions that can suppress the coupled vibration.

The stationary vehicle-guideway self-excited instability problem should be solved urgently, as maglev systems are rapidly approaching commercial application. A better understanding of the principle underlying the coupled vibration instability problem is essential to designing effective control algorithms that can suppress this instability. A quality vehicle-guideway coupled model is an essential pre-requisite for studying the principles underlying the coupled vibration instability problem. However, an extremely complex vehicle model is not necessary for investigating the stationary vehicle-guideway self-excited vibration problem, but a detailed and precise model of the control system is necessary. A detailed multi-electromagnetic-bridge coupled model including the control system may be required, and the suspending force should not be described as simple spring-damper systems. In addition, the constraints of control voltage and the nonlinearity of the magnetic forces should be taken into account in the dynamic model.

To enhance the safety of maglev systems, further work is needed to develop an understanding of the moving vehicle-bridge coupled vibration problem and the effect of guideway irregularity. The models investigated should include physical constraints such as the maximum tolerance for the suspension-gap error, and the maximum control voltage and maximum capability of the power supply system in the vehicle. Within these constraints, there is the possibility to examine the effectiveness of a range of different control algorithms. Work is also needed to further improve the ride comfort. Active control of both the primary and secondary suspension systems could be considered for use in maglev vehicles to enhance the ride comfort.

It is important that efforts are made to determine the optimal design of the guideway, as this is a key factor influencing coupled vibration problems. Some important parameters should be considered when designing maglev bridges, such as the bridge resonance frequencies, the bridge damping, and the bridge span, so that the natural frequency of most suspension controllers can be avoided. In addition, TMDs (Tuned Mass Dampers) have been adopted to absorb the vibration energy of bridges in rail systems, and these could also be considered for maglev systems.[108]

The most economical way to minimize the coupled vibration problem is to improve the levitation control algorithms. However, this is a difficult task, as all algorithms must guarantee the stability of the levitation to avoid a catastrophic failure. As the EMS maglev systems are inherently unstable, this will be difficult to achieve. Ideally, the vibration control algorithms should suppress both the stationary vehicle-guideway self-excited vibration and the moving vehicle-bridge coupled vibration. Achieving this goal will require considerable research effort.

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