

Article

Study on Coupled Vertical Vehicle-Bridge Dynamic Performance of Medium and Low-Speed Maglev Train

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Abstract: The levitation stability of maglev trains is determined by the interaction of vehicle-bridge dynamic characteristics. The state change of vehicle and track beam will affect the dynamic performance of maglev trains. In order to study the levitation characteristics of maglev trains, a coupled vehicle-bridge dynamic model based on an elastic beam was established to study the influence of beam stiffness and vehicle load on the dynamic performance of the maglev system. In the form of numerical simulation, the time-domain characteristics of key characteristic variables, such as levitation gap and vertical deflection of track beam, under different working conditions of stiffness and load were analyzed. The simulation shows that the levitation system can smoothly converge to the stable value under each working condition, which indicates the rationality of the field test. Based on the Shanghai Lingang medium-and-low-speed maglev test line, the maglev test was carried out, and the time-domain and frequency-domain characteristics of the above key variables were analyzed based on the measured data. The results show that the fluctuation of the levitation gap was affected by load and stiffness, and the law was consistent with the simulation results. The increase in load or the decrease in beam stiffness would lead to an increase in vertical deflection and vibration of the track beam. However, the train could still maintain good levitation performance under the above extreme conditions, which verified the reliability of the levitation system and the correctness of the simulation model. The conclusion of this paper can provide a reference for the design of the levitation system and track line of medium-and-low-speed maglev train.

Keywords: low-to-medium-speed maglev; coupled vehicle-bridge system; dynamic response; vertical vibration



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1. Introduction

Medium and low-speed maglev trains have been gradually introduced in cities due to their advantages of strong climbing ability, small turning radius, and low noise. At present, four commercial operation lines of medium and low-speed maglev trains have been built in the world, which are distributed across Japan, South Korea, and Changsha and Beijing in China. Different from the traditional wheel-rail train operation mode, a certain gap is maintained between the train and the track so that maglev trains are not limited by sliding friction [1–3]. Through electromagnetic induction between the electromagnet on the vehicle suspension frame and the coil reaction plate on the track, a generated levitation force is generated to levitate the maglev train. In the process of operation, the loss of train stability or collision of rail will occur due to uneven load of vehicle or track irregularity. Therefore, it is of great significance to study the dynamic performance of the coupled vehicle-bridge system for the smooth operation of maglev trains.

Elevated guideways are widely applied in maglev systems. Compared with the traditional wheel-rail train, bridges are also an important part of maglev systems in addition to the track and vehicle. Therefore, the train-track-bridge system is used as a research

object in many studies. Wang D. X. et al. [4] proposed a vertical dynamic interaction model of medium and low-speed maglev train-track-bridge system and discussed the vibration characteristics of F-type track and the influence mechanism of track structure on the dynamic bridge response. Li X. et al. [5] developed a vertical coupling vibration simulation program for maglev vehicles and simply supported beam system, compared the simulation results with the dynamic response of field test. Li M. [6] and Zhang M. [7] carried out the dynamic test of the train-track-bridge system for the new suspension bogie with a central air spring. Liu D. J. et al. [8] established a dynamic coupling model of medium and low-speed maglev vehicle-controller-bridge systems and studied the vertical dynamic response of vehicle and bridge when trains run at different speeds and different vehicle loads. Lu H. Y. et al. [9] established coupled vehicle-bridge dynamic model to analyze the vibration response characteristics in the floating stage. Kim et al. [10] integrated a three-dimensional vehicle model, multi-modality guideway model, and feedback suspension control algorithm to study the dynamic characteristics of vehicles and rail at low speed.

As an important infrastructure of the maglev line, the characteristics of the bridge itself were closely related to vehicle-bridge coupling vibration performance [11,12]. Wang et al. [13] studied the dynamic interaction between medium and low-speed maglev trains and bridges with different vertical deflection ratios and proposed the allowable deflection ratios for bridges with different spans. Liang L. et al. [14] analyzed the vertical dynamic characteristics and vertical resonance mechanism of maglev train-bridge systems with different beam heights. Geng J. [15] proposed the limit values of key design parameters, including dynamic coefficient, natural frequency, vertical stiffness, transverse stiffness, and bending angle of beam end, suitable for medium and low-speed maglev operation. Li X. Z. et al. [16] studied the vibration effects of a simply supported beam and continuous beam on vehicles and bridges. Lee J. S. [17] established the dynamic control equation of coupled vehicle-guideway model and controller and studied the dynamic performance of vehicle speed, deflection ratio, span length, span continuity, and damping ratio.

At present, there are many studies on the dynamic performance of the vehicle-track coupling system. On the one hand, numerical simulations are carried out by establishing the vehicle-track coupling model combined with the controller, and the dynamic response of the system with various influencing factors is analyzed. On the other hand, field tests under different working conditions are carried out to evaluate dynamic performance [18]. Due to the limitation of field tests, the analysis of many influencing factors of coupled vehicle-bridge systems has only been limited to numerical simulation [3,11]. In this paper, a dynamic model of coupled vehicle-bridge systems based on an elastic beam was established, and the dynamic system response with the influence of bridge stiffness and vehicle load was simulated and analyzed. The single-span steel beam (24.94 m) was tested in Shanghai Lingang medium and low-speed maglev base. According to the test data, the time and frequency domain characteristics of vehicles and bridges under different working conditions were analyzed, and the simulation results were verified. Due to the large fluctuation of the suspension gap in the static levitation stage, the phenomenon of vehicle-bridge coupling vibration is more likely to occur [10]. In this paper, the dynamic performance of the train in the static levitation process was analyzed. In addition, the simulation and test results could provide a reference for the design and formulation of maglev traffic regulations.

The overall structure of this paper is as follows: in the second section, the coupled vehicle-bridge dynamic model is established based on the flexible beam, and the open-loop instability of the suspension system is explained with the Hurwitz criterion. Moreover, the feedback control algorithm based on voltage control is given for further simulation analysis. In the third section, based on the actual vehicle and track beam parameters, numerical simulation is carried out for the key characteristics of vehicle and track, respectively, and the dynamic response of the system is analyzed. In the fourth section, the relevant scheme designed for the test is given firstly, and then the test analysis is carried out combined with

the change of vehicle load and track-beam stiffness. Finally, the relevant conclusions are contained in the fifth section.

2. Coupled Vehicle-Bridge System Considering Elastic Beam

As the critical system of maglev trains, the magnetic coupled vehicle-bridge system, determining the safety and stability of normal operation, is the foundation of vehicle suspending on the bridge [19]. The operation diagram of a maglev train on a line is shown in Figure 1. The whole vehicle body is supported by the magnetic levitation force generated by several suspension frames. The force is dynamically adjusted by the suspension controller to keep the gap between the electromagnet in the suspension frame and the track near the expected value.

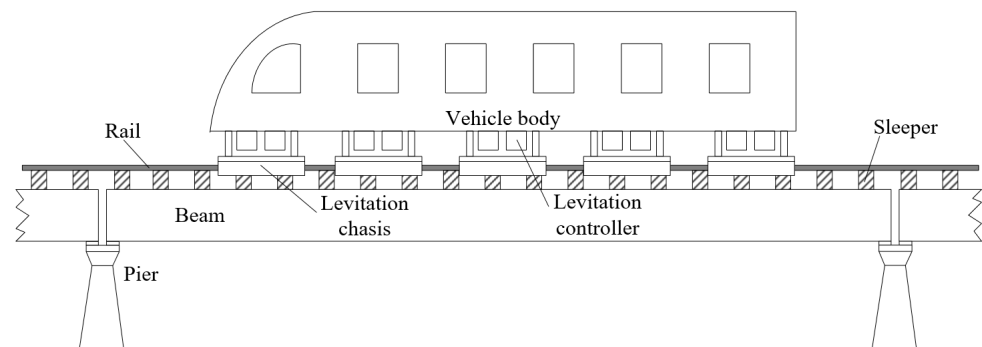


Figure 1. Maglev train on an operation line.

A suspension frame consists of four suspension points, two of which on each side of the vehicle. According to the decoupling analysis of suspension frames, the coupled vehicle-bridge system can be regarded as multiple independent single-point suspension systems. When the train is on the steel beam with a small damping coefficient, whether it is in static levitation or at low speed, the coupled vibration phenomenon can be caused easily [20]. In order to study this phenomenon, a single-point suspension system model considering elastic beam is established, as shown in Figure 2.

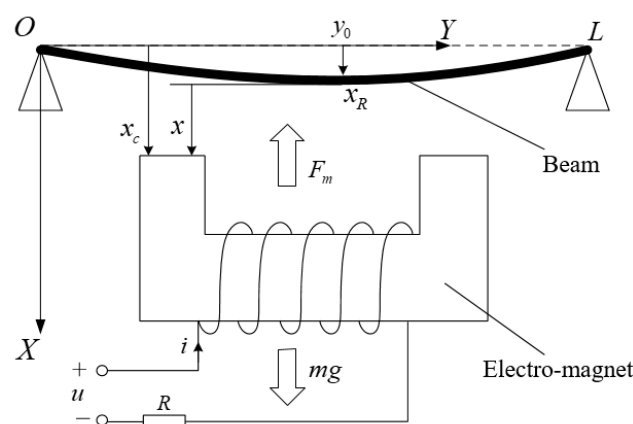


Figure 2. Single-point suspension system considering elastic beam.

In Figure 2, y_0 is the displacement of the electromagnet from the coordinate origin (along the OY direction), L is the beam span, x_R is the vertical deformation of the elastic beam (along the OX direction), x_c is the vertical displacement of the electromagnet, x is the suspension gap, m is the mass of electromagnet, F_m is the levitation force, u is the voltage of electromagnet coil, i is the control current, R is the coil resistance, N is the number of

winding turns, and S is the effective pole area of the magnet, while Vacuum permeability is $\mu_0 = 4\pi \times 10^{-7}$ H/m. The levitation force provided by a single point can be expressed as:

$$F_m(t) = \frac{\mu_0 N^2 S}{4} \left(\frac{i(t)}{x(t)} \right)^2, \quad (1)$$

where $x(t) = x_c(t) - x_R(t)$; the deviation between the vertical displacement of the electromagnet and the vertical deformation of the beam is the actual suspension clearance. The dynamic equation of a single-point electromagnet can be described as:

$$m\ddot{x}_c(t) = (m + M)g - F_m(t), \quad (2)$$

where M is the mass of carriage. The voltage equation of electromagnet can be expressed as:

$$u = Ri(t) + \frac{\mu_0 N^2 S}{2x(t)} \frac{di(t)}{dt} - \frac{\mu_0 N^2 S}{2x^2(t)} \frac{dx(t)}{dt}. \quad (3)$$

Considering that the track is a simple supported beam, the coordinate $x_R(y, t)$ of any point on the beam satisfies the Euler–Bernoulli dynamic equation [21–23]:

$$E_r I_r \frac{\partial^4 x_R(y, t)}{\partial y^4} + \rho_r \frac{\partial^2 x_R(y, t)}{\partial t^2} + \varphi_r \frac{\partial x_R(y, t)}{\partial t} = f(y, t), \quad (4)$$

where the elastic modulus and section inertia of the beam are E_r and I_r respectively, ρ_r is the linear density of the beam, φ_r is the equivalent damping coefficient of the beam, and $f(y, t)$ is the external force on the beam, which can be approximately expressed as:

$$f(y, t) = F_m \delta(y - y_0). \quad (5)$$

According to the vibration theory of beam, only when the excitation energy is very high can the vibration of high-order mode appear [21]. Therefore, vibration analysis under the first mode is usually considered [22,23]. In this paper, only the first mode is considered, and the elastic beam model under the first mode is obtained by modal analysis method [24]:

$$x_R(y, t) = \sigma_1(y) q_1(t), \quad (6)$$

where $\sigma_1(y)$ is the first mode function, $q_1(t)$ is the time-dependent amplitude of beam in the first mode. The first mode function $\sigma_1(y)$ can be expressed as:

$$\sigma_1(y) = \sqrt{\frac{2}{m_r}} \sin\left(\frac{\pi}{L} y\right), \quad (7)$$

where m_r is a constant, and its value is the mass of beam, which can be obtained by $m_r = \rho_r L$. Equations (5) and (6) are introduced into Equation (4), and the two sides of Equation (4) are integrated from 0 to L . The following formula is finally obtained:

$$\ddot{q}_1(t) + 2\tau_1 \omega_1 \dot{q}_1(t) + \omega_1^2 q_1(t) = \sqrt{\frac{2}{m_r}} \sin\left(\frac{\pi}{L} y_0\right) F_m, \quad (8)$$

Since the beam span is much longer than the length of the electromagnet, the electromagnet is regarded as a point on the beam, and the center of the electromagnet is located in the center of the track, that is $y_0 = L/2$. Where τ_1 is the damping ratio of the first mode, ω_1 is the natural frequency of the first mode, it can be calculated as:

$$\omega_1 = \left(\frac{\pi}{L}\right)^2 \sqrt{\frac{E_r I_r}{\rho_r}}, \quad (9)$$

Both sides of Equation (8) are multiplied by $\sigma_1(y)$, let $K_1 = 2\sigma_1^2(y_0)$, and Equation (8) can then be transformed into:

$$\ddot{x}_R(t) + 2\tau_1\omega_1\dot{x}_R(t) + \omega_1^2x_R(t) = K_1F_m. \quad (10)$$

Finally, the coupled vehicle-bridge system model considering elastic beam in the first mode is obtained by combining the elastic beam model with the single-point suspension model:

$$\begin{cases} x = x_c - x_R, \\ F_m = K_2 \frac{i^2}{x^2}, \\ m\ddot{x}_c = (m + M)g - F_m, \\ u = Ri + \frac{2K_2}{x}i - \frac{2K_2i}{x^2}\dot{x}, \\ \ddot{x}_R(t) + 2\tau_1\omega_1\dot{x}_R(t) + \omega_1^2x_R(t) = K_1F_m, \end{cases} \quad (11)$$

where:

$$K_1 = \left(\sqrt{\frac{2}{m_r}} \sin\left(\frac{\pi}{L}y_0\right) \right)^2, \quad K_2 = \frac{\mu_0 N^2 S}{4}.$$

The state vector is $Z = (z_1, z_2, z_3, z_4, z_5)^T = (x_c, \dot{x}_c, x_R, \dot{x}_R, i)^T$, where z_1 is the vertical displacement of the electromagnet, z_2 is the vertical velocity of the electromagnet, z_3 is the vertical displacement of the beam, z_4 is the vertical velocity of the beam, and z_5 is the current of electromagnet coil. The state-space equation of open-loop coupled vehicle-bridge levitation system under the first mode is as follows:

$$\begin{cases} \dot{z}_1 = z_2, \\ \dot{z}_2 = \frac{m+M}{m}g - \frac{K_2}{m}\left(\frac{z_5}{z_1-z_3}\right)^2, \\ \dot{z}_3 = z_4, \\ \dot{z}_4 = K_1K_2\left(\frac{z_5}{z_1-z_3}\right)^2 - 2\tau_1\omega_1z_4 - \omega_1^2z_3, \\ \dot{z}_5 = \left(\frac{z_5}{z_1-z_3}\right)(z_2 - z_4) - \frac{R}{2K_2}(z_1 - z_3)z_5 + \frac{z_1-z_3}{2K_2}u. \end{cases} \quad (12)$$

The premise of stability analysis of Equation (12), based on the Hurwitz criterion, is to solve the singularities of the system. Let $\dot{z} = \begin{pmatrix} \dot{z}_1 & \dot{z}_2 & \dot{z}_3 & \dot{z}_4 & \dot{z}_5 \end{pmatrix}^T = 0$:

$$\begin{cases} z_2 = 0, \\ \frac{m+M}{m}g - \frac{K_2}{m}\left(\frac{z_5}{z_1-z_3}\right)^2 = 0, \\ z_4 = 0, \\ K_1K_2\left(\frac{z_5}{z_1-z_3}\right)^2 - 2\tau_1\omega_1z_4 - \omega_1^2z_3 = 0, \\ \left(\frac{z_5}{z_1-z_3}\right)(z_2 - z_4) - \frac{R}{2K_2}(z_1 - z_3)z_5 + \frac{z_1-z_3}{2K_2}u = 0. \end{cases} \quad (13)$$

The singularity of Equation (13) can be shown as two solutions, $z^0 = (z_1^0, z_2^0, z_3^0, z_4^0, z_5^0)^T =$:

$$\begin{aligned} (1) & \left(\frac{K_1(m+M)g}{\omega_1^2} + \frac{u}{R} \sqrt{\frac{K_2}{(m+M)g}}, 0, \frac{K_1(m+M)g}{\omega_1^2}, 0, \frac{u}{R} \right)^T \\ (2) & \left(\frac{K_1(m+M)g}{\omega_1^2} - \frac{u}{R} \sqrt{\frac{K_2}{(m+M)g}}, 0, \frac{K_1(m+M)g}{\omega_1^2}, 0, \frac{u}{R} \right)^T \end{aligned}$$

Since the two solutions have the same characteristics corresponding to the equilibrium point, either of them can be chosen for stability analysis, and solution (1) was selected here.

At the equilibrium point z^0 , the system is linearized as $\dot{z} = A(z^0)(z - z^0)$, where $A(z^0)$ is the Jacobian matrix of the system:

$$A(z^0) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ a_{21} & 0 & a_{23} & 0 & a_{25} \\ 0 & 0 & 0 & 1 & 0 \\ a_{41} & 0 & a_{43} & -2\tau_1\omega_1 & a_{45} \\ 0 & \sqrt{\frac{(m+M)g}{K_2}} & 0 & -\sqrt{\frac{(m+M)g}{K_2}} & a_{55} \end{bmatrix}, \quad (14)$$

where:

$$\begin{aligned} a_{21} &= -a_{23} = \frac{2R}{mu\sqrt{K_2}}((m+M)g)^{\frac{3}{2}}, \\ a_{25} &= -\frac{2R(m+M)g}{mu}, \\ a_{41} &= -\frac{2K_1R}{u\sqrt{K_2}}((m+M)g)^{\frac{3}{2}}, \\ a_{43} &= \frac{2K_1R}{u\sqrt{K_2}}((m+M)g)^{\frac{3}{2}} - \omega_1^2, \\ a_{45} &= \frac{2RK_1(m+M)g}{u}, \\ a_{55} &= -\frac{u}{2\sqrt{K_2(m+M)g}}. \end{aligned}$$

The characteristic equation of Equation (14) is obtained by $|\lambda E - A|$:

$$J(\lambda) = \lambda^5 + b_1\lambda^4 + b_2\lambda^3 + b_3\lambda^2 + b_4\lambda + b_5, \quad (15)$$

According to the Hurwitz stability criterion [25], the necessary and sufficient condition for the stability of linear systems is that the coefficients of characteristic polynomials are all positive, that is $b_1 > 0, b_2 > 0, \dots, b_5 > 0$. When one of the coefficients is negative, it can be determined that the system is unstable. Considering the complexity of the fifth-order model, only the constant term b_5 is discussed:

$$b_5 = -\frac{(m+M)gR\omega^2}{mK_2}$$

Since $b_5 < 0$, the instability of the system can be judged, and feedback control law is needed to control the air gap.

Taking air gap deviation $z_1 - z_3 - x_{ref}$, electromagnet velocity z_2 , current z_5 three states as feedback control loop [26]. Therefore, the feedback control law is:

$$u = u_{ec} + k_g(z_1 - z_3 - x_{ref}) + k_s z_2 + k_c z_5 \quad (16)$$

where, u_{ec} is the voltage at equilibrium, x_{ref} is the target air gap, k_g, k_s , and k_c are the feedback factor of each loop, respectively. At equilibrium, $z_2^0 = 0, z_1^0 - z_3^0 = x_{ref}, z_5^0 = x_{ref}\sqrt{(m+M)g \cdot K_2^{-1}}$, the voltage, u_{ec} , can be described as:

$$u_{ec} = u - k_c z_5^0 = (R - k_c)z_5^0 = (R - k_c)x_{ref}\sqrt{(m+M)g \cdot K_2^{-1}} \quad (17)$$

Substituting Equation (16) into Equation (12), the state equation of the closed-loop coupled maglev vehicle-bridge system can be obtained:

$$\begin{cases} \dot{z}_1 = z_2, \\ \dot{z}_2 = \frac{m+M}{m}g - \frac{K_2}{m}\left(\frac{z_5}{z_1-z_3}\right)^2, \\ \dot{z}_3 = z_4, \\ \dot{z}_4 = K_1K_2\left(\frac{z_5}{z_1-z_3}\right)^2 - 2\tau_1\omega_1 z_4 - \omega_1^2 z_3, \\ \dot{z}_5 = \left(\frac{z_5}{z_1-z_3}\right)(z_2 - z_4) - \frac{R}{2K_2}(z_1 - z_3)z_5 + \frac{z_1-z_3}{2K_2}\left(u_{ec} + k_g(z_1 - z_3 - x_{ref}) + k_s z_2 + k_c z_5\right). \end{cases} \quad (18)$$

3. Numerical Simulations

During the operation of maglev trains, the change of passenger capacity leads to a change in train load. As a key variable of maglev systems, load affects the overall dynamic performance of the system. In addition, the high cost of bridge construction in maglev systems has always been a disadvantage. As a key parameter of the bridge, the stiffness largely determines the cost. Therefore, it is necessary to study how bridge stiffness affects the dynamic response of the system, so as to pave the way for judging the lower limit of the bridge stiffness on the premise of stable operation. The influence of bridge characteristics and vehicle load on the vehicle-bridge coupling vibration system was studied through numerical analysis on the Matlab/Simulink platform. The physical parameters of the coupled maglev vehicle-bridge system are shown in Table 1. In order to form mutual verification with the field test, the real parameters of a maglev train were used for the simulation analysis.

Table 1. Physical parameters value of a maglev coupled vehicle-bridge system.

Symbol	Quantity	Value
m	Mass of electromagnet	500 kg
x_{ref}	Target gap	0.009 m
L	Span of Beam	24.94 m
E_r	Elastic modulus	206 GPa
R	Magnetic resistance	4 Ω
τ_1	Damping ratio of the bridge	0.005
μ_0	Vacuum permeability	$4\pi \times 10^{-7} \text{ H}\cdot\text{m}^{-1}$
S	electromagnetic pole area	0.024 m ²
N	Turn Ratio	500

In order to analyze the influence of vehicle load M on vehicle-bridge coupling vibration, the dynamic system response under no load $M = 33 \text{ t}$ and overload $M = 39 \text{ t}$ was analyzed, respectively. It can be seen from Figure 3a–d that the airgap, bridge deflection, acceleration of electromagnet, and bridge tended to be stable, which indicates that the stable suspension could be maintained no matter if there is no load or an overloaded mass. Comparing the dynamic response changes under different loads, it can be seen in Figure 3a that during 1–3 s the response speed of the gap was decreased due to the increase in load. In order to adjust the gap dynamically, the levitation force was increased to balance with gravity, but the real-time change of levitation force was weakened. Therefore, as shown in Figure 3c,d, the vertical acceleration of electromagnet and bridge increased. In addition, in Figure 3b, the static deflection of the mid-span bridge was about 0.545 mm under no-load conditions, and it was about 0.642 mm when overloaded, with an increase of 0.097 mm.

In the field test, the stiffness of a bridge is usually changed by adjusting beam height. The change of beam height can be regarded as the change of bridge quality. Therefore, at full stiffness, the mass of the steel beam m_r was defined as 50 tons, and the section inertia I_r was 0.9341. After reducing the stiffness (low stiffness), the mass of the steel beam was 45 tons, and the section inertia was 0.7081. The dynamic response of the system under different stiffness is shown in Figure 4.

The response difference of low stiffness compared with full stiffness shows that the fluctuation amplitude of the gap was larger, as shown in the subgraph of Figure 4a, but there was no significant difference in response speed. In Figure 4b, the mid-span static deflection of the bridge was 0.545 mm at full stiffness and 0.719 mm at low stiffness, with an increase of 0.174 mm. It can be seen from Figure 4c,d that the vertical vibration of the electromagnet and bridge increased due to the decrease in stiffness.

Through the simulation analysis, it could be concluded that the increase in load or the decrease in stiffness would have a negative impact on the suspension stability and riding comfort of maglev trains. It indicates that bridge characteristics and vehicle load have a significant influence on the dynamic response of coupled vehicle-bridge systems, which are the important factors to study the vertical dynamic performance of the system.

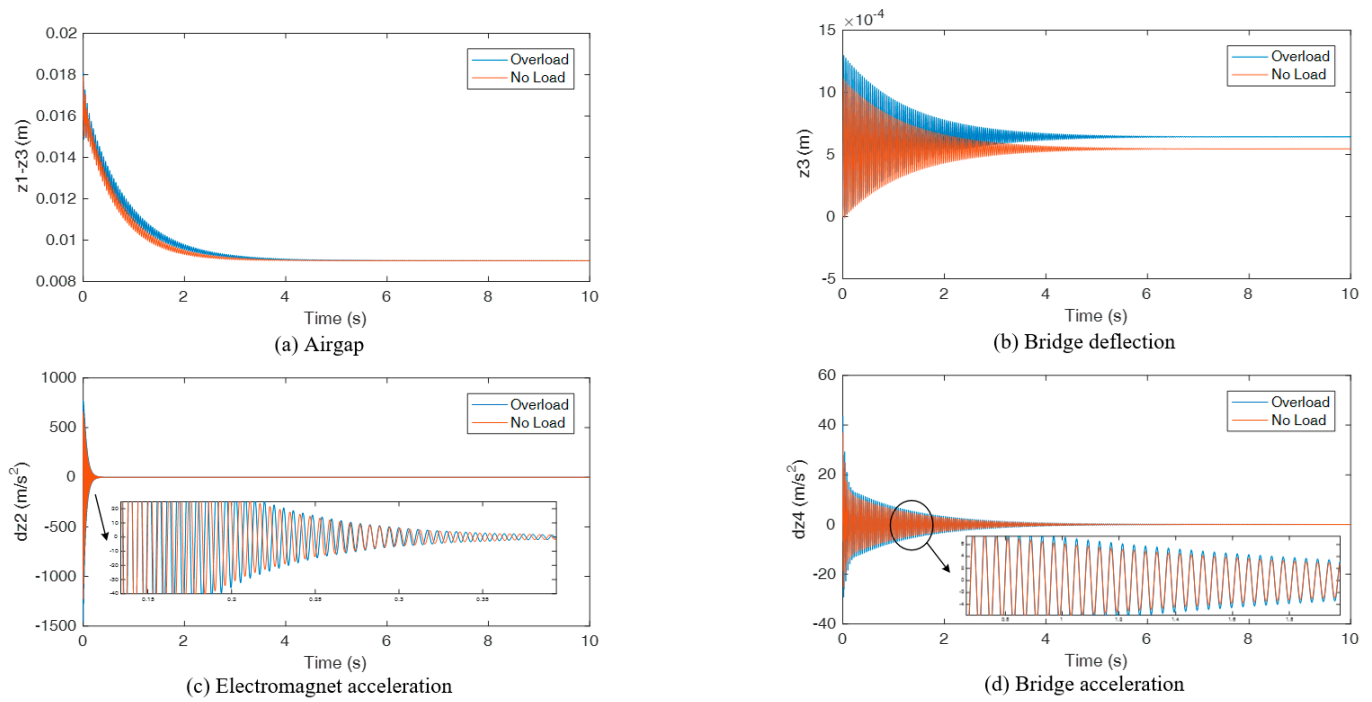


Figure 3. Dynamic response of the system with different loads.

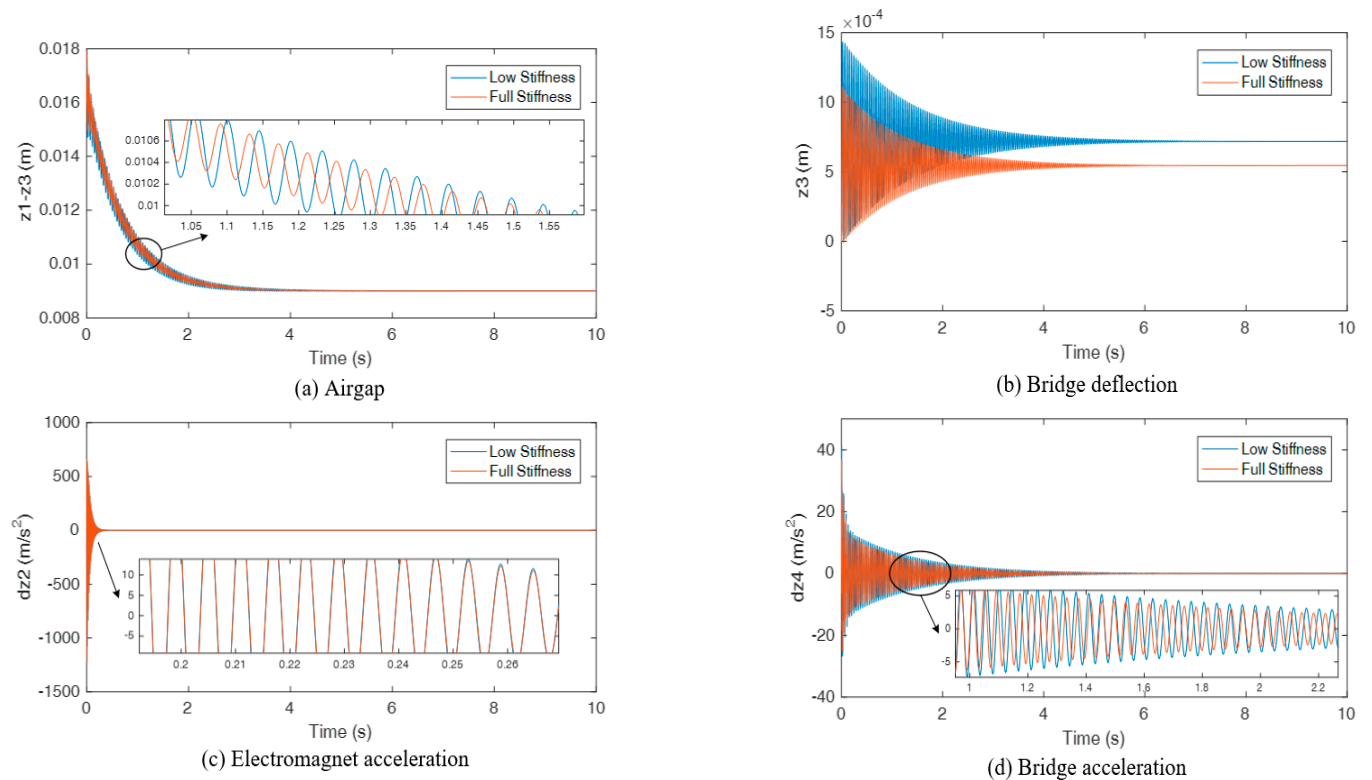


Figure 4. Dynamic response of the system with different stiffness.

4. Test Results and Analysis

To further analyze the actual influence of vehicle load and bridge stiffness on the dynamic performance of a magnetic coupled vehicle-bridge system, the field test of steel beam was carried out in Shanghai Lingang medium using a low-speed maglev test base. Since the test parameters were consistent with the physical parameters of the simulation,

the above simulation results that the suspension system always converged to the target gap (9 mm) under different conditions with different loads and stiffness proved the rationality of the test.

4.1. Test Scheme

In order to facilitate the comparative analysis of test and simulation, the acquisition and analysis of test data are also carried out according to different loads and stiffness, and the sampling frequency was set to 1000 Hz. The coupled low-to-medium-speed maglev train and steel beam system in the field test are shown in Figure 5. The arrangement of test points is shown in Figure 6. There was one vibration acceleration test point and one vertical dynamic displacement test point on the suspension frame, which were located at the connection between the air spring and the support on the second suspension frame (without a transverse sliding table). In addition, there were four three-channel gap test points arranged on each gap sensor on the suspension bogie, which were used to collect the relative gap between electromagnet and track. As for the steel beam, one vibration acceleration test point (using ULT2008 built-in IC piezoelectric acceleration sensor) and one vertical dynamic displacement test point (using PT8510 pull-wire displacement sensor) were arranged at the lower surface center of the mid-span bridge. The sensors in the field test are shown in Figure 7.



Figure 5. Coupled low-to-medium-speed maglev train and steel beam system in the field test.

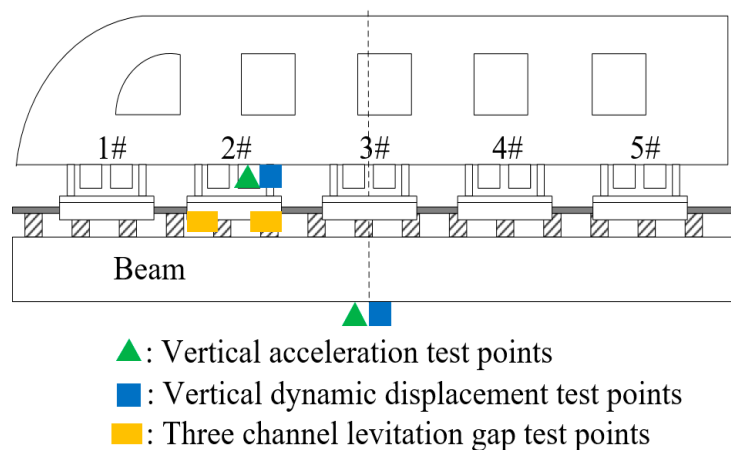
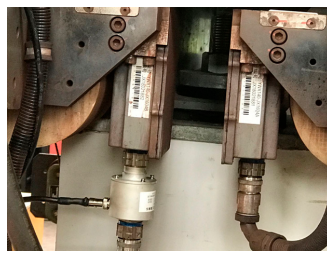


Figure 6. Arrangement of test points.



(a) Vertical vibration test on the suspension bogie



(b) Three-channel gap test on the suspension bogie



(c) Vertical displacement and vibration test of bridge

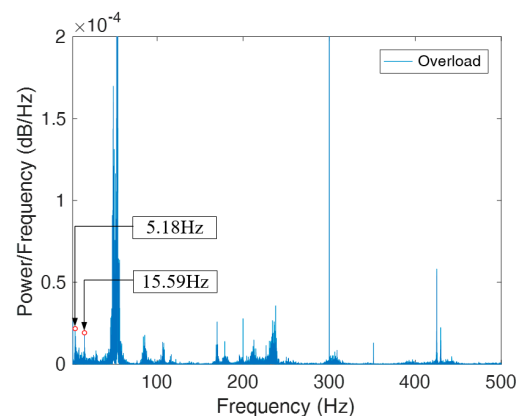
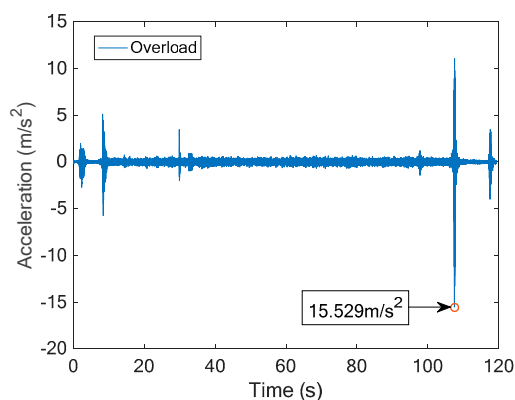
Figure 7. Sensors in the field test.

4.2. Parametric Analysis

In order to study the influence of vehicle load and bridge stiffness on the dynamic performance of the coupled vehicle-bridge system, the responses of vertical vibration of suspension bogie, airgap, vertical vibration, and vertical deflection of the bridge were analyzed in depth.

4.2.1. Vehicle Load

Effects of vehicle load on the vertical acceleration of suspension bogie are shown in Figure 8. It can be seen from the time domain diagram that the period with obvious acceleration amplitude (such as multiple peaks) represented the levitation (or landing) of the suspension bogie. Since several suspension bogies work orderly, there were multiple peaks in the diagram. The peak with maximum amplitude was generated by the second suspension bogie (vertical acceleration test point), and the relatively smooth area during 40–90 s was the response of complete suspension. It can be seen that the maximum vertical accelerations under overload and no-load conditions were 15.529 m/s^2 and 8.279 m/s^2 , respectively. Accordingly, the maximum vertical acceleration of the suspension bogie increased by 7.25 m/s^2 when the load was increased by 6 tons. Since the levitation force could not adapt to the change of load, vertical acceleration was generated. However, the load change in unit time was aggravated when the load increased, and the adaptability of suspension force to load change was further weakened, it led to the vertical acceleration and airgap change. The vertical acceleration of the suspension bogie increased when overloaded, which confirmed the simulation results in Figure 3c. In addition, in Figure 8b, the vibration acceleration within 40 s to 100 s was larger than that when overloaded. It can be regarded that the instantaneous point dropping or rail smashing occurred during static levitation, which causes track excitation, and it was transmitted to suspension bogie by the levitation force.



(a) Overload

Figure 8. Cont.

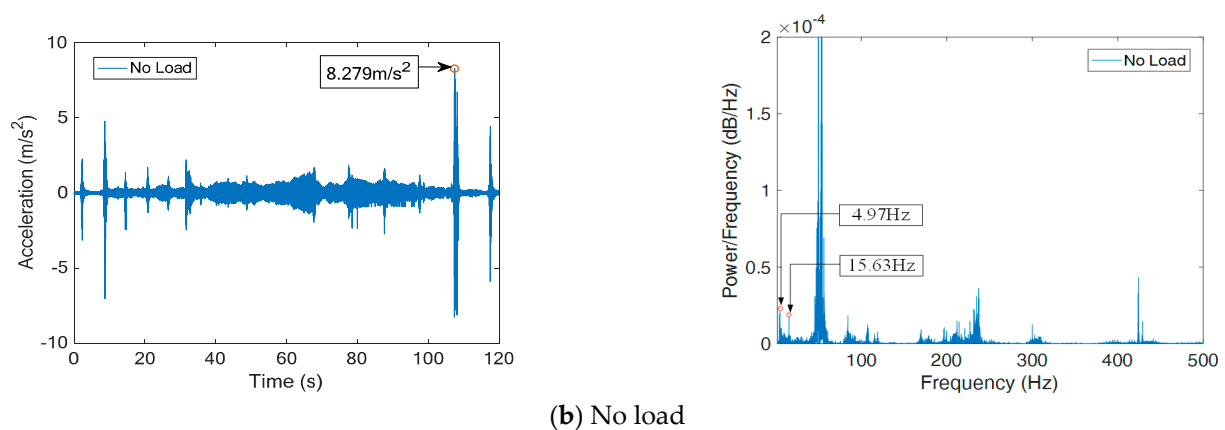


Figure 8. Effects of vehicle load on the vertical acceleration of suspension bogie.

According to the train-bridge coupling state, the whole static levitation process is divided into three stages: floating, levitation, and landing. In order to accurately analyze the spectrum relationship, only the suspension stage was analyzed. It can be seen from Figure 8 that the load had almost no effect on the vibration spectrum. The first-order vibration frequency was 5.18 Hz when overloaded and 4.97 Hz with no load. The frequency values of the two conditions were similar.

In Figure 9, from the curve change trend within 20–40 s, it can be seen that the response speed of overload was much slower than that of the no-load condition, which was consistent with the law shown in Figure 3a. The no-load state was finally stable near the ideal gap (8.5 mm), while the overload state had a steady-state error of about 1 mm. It indicates that the real-time and accuracy of levitation control were reduced, and the response speed of the airgap was slowed down due to the increase in load. In order to overcome the adverse effects of load, the reliability and robustness of the suspension control algorithm should be further improved.

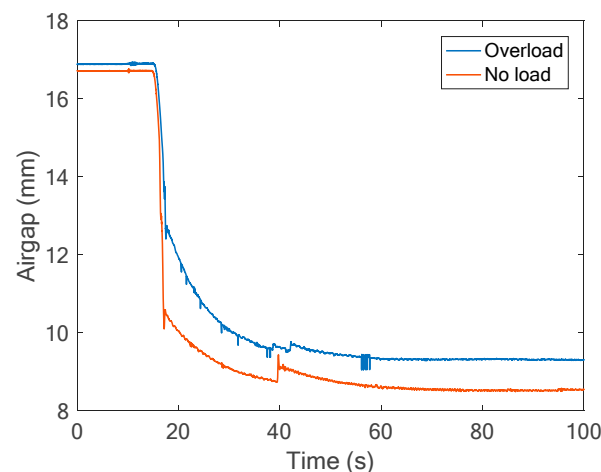


Figure 9. Effect of vehicle load on the airgap.

As shown in Figure 10, the vertical vibration of bridge under different loads was analyzed in the time and frequency domains. The maximum vertical acceleration of the bridge was 1.177 m/s^2 under overload conditions and 0.776 m/s^2 under no-load conditions. It indicates that the vibration acceleration amplitude of the bridge increased by 0.401 m/s^2 when the load was increased by 6 tons. Therefore, the influence of load on the vertical acceleration of the suspension bogie was more significant than that of the bridge, which indicates the rigidity of the suspension bogie structure was smaller than that of the bridge. According to the frequency domain diagram, it can be seen that the energy near 70 Hz was

high, which represents the forced vibration of the bridge caused by track excitation, and the energy in the overloaded condition was higher than that of the no-load condition. It could be judged that the increase in load made the levitation force increase, and the external excitation of the track was further enhanced. In addition, the first natural frequency of the bridge was about 7.1 Hz. According to the code for design of medium and low-speed maglev traffic (CJJ/T 262-2017), the vertical first natural frequency of bridge design should be greater than $64/L$, where L is the span of the bridge 6. The measured results show that the bridge had enough vertical stiffness.

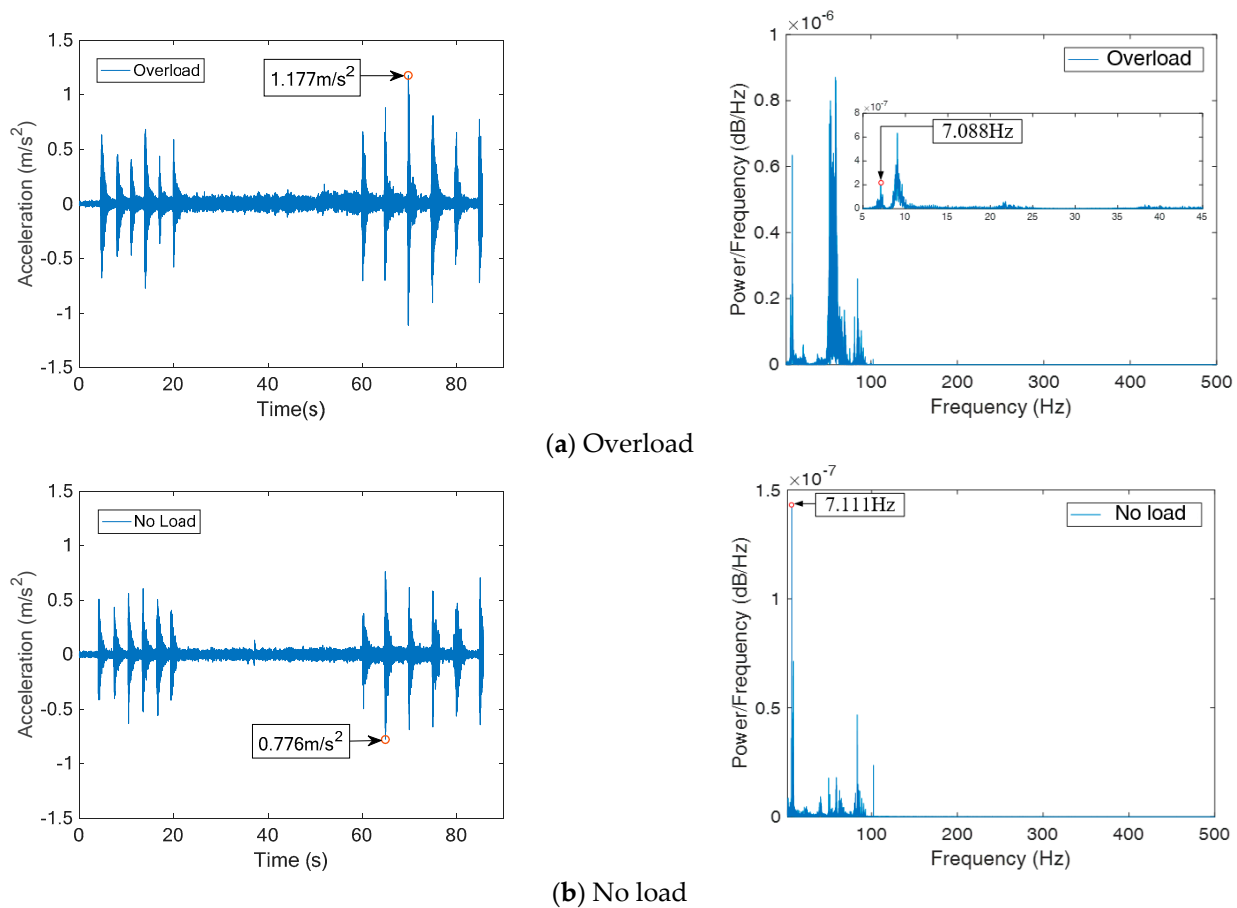


Figure 10. Effect of vehicle load on the vertical acceleration of the bridge.

Figure 11 shows the effect of load on the vertical deflection of bridge. In Figure 11a, the wire-type displacement sensor is arranged in the middle of the single-span steel beam, and the initial value was 42 mm. In each static levitation test, the train ran to the middle of the bridge. Under overload conditions, the displacement became 38.41 mm, and the corresponding maximum static deflection of the bridge was about 3.59 mm. Under the no-load condition, the displacement became 39.59 mm, and the maximum static deflection was about 2.41 mm, indicating that the maximum static deflection of the bridge increased by 1.18 mm when the load was increased by 6 tons. According to the static analysis, when the uniformly distributed load was located in the middle of the simple elastic supported beam, the maximum static deflection of the bridge can be expressed as follows:

$$W_{\max} = \frac{qbL^3}{384EI} \left(8 - \frac{4b^2}{L^2} + \frac{b^3}{L^3} \right) \quad (19)$$

where W is static deflection, q is the mass of distributed load, and b is the length of distributed load. Assuming that the load distribution of a maglev train is uniform, the greater the mass, the greater the maximum static deflection of the bridge. Figure 11b shows

the relative change of the vertical deflection of the bridge. Due to the existence of bridge vibration, the mid-span deflection changed dynamically with time, and the deflection under overload was greater than that under no-load, which was consistent with the law that vertical acceleration of bridge under overloaded conditions is greater, as shown in Figure 10, the law is shown in Figure 3b.

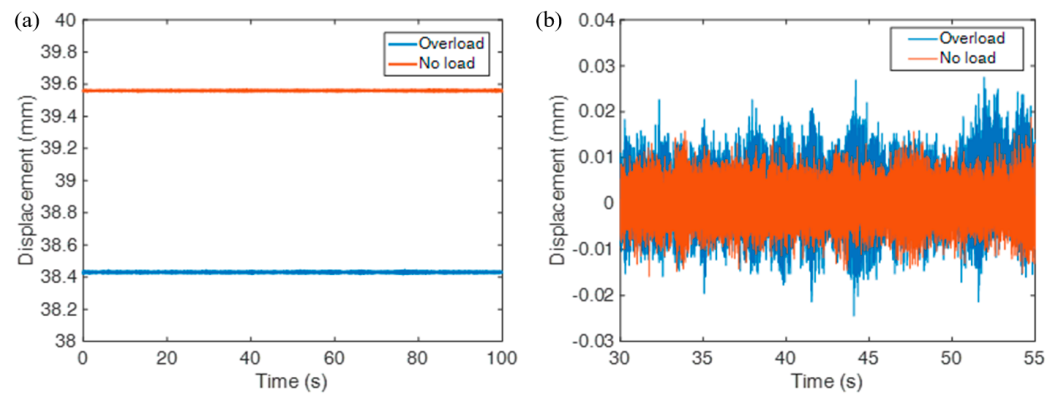


Figure 11. Effect of load on the vertical deflection of the bridge: (a) absolute displacement and (b) relative displacement.

4.2.2. Bridge Stiffness

Under the premise of consistent vehicle load, the change of bridge stiffness directly affected the deflection of the bridge. As shown in Figure 12a, the initial vertical displacement was set as 42 mm. The average deflection of the bridge was 38.64 mm at low stiffness and 39.58 mm at full stiffness. In this test, the bridge stiffness was changed by changing beam height. The decrease in beam height led to a decrease in section inertia. According to Equation (19), there is an inverse relationship between the section inertia and the static deflection of a bridge; thus, the reduction in stiffness would increase the mid-span deflection (about 0.94 mm), which was also reflected in the numerical results in Figure 4b. Due to the dynamic change of levitation force during static levitation, the vertical deflection of bridge changes in real-time under the influence of levitation force; as shown in Figure 12b, the fluctuation bandwidth of bridge deflection was wider when the stiffness was low.

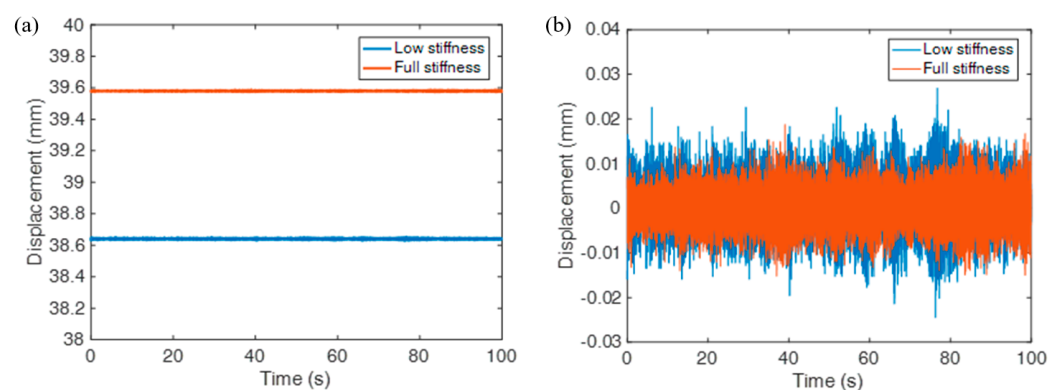


Figure 12. Effect of stiffness on the vertical displacement of the bridge: (a) absolute displacement and (b) relative displacement.

In the levitation process of the test train, the time-domain vibration waveform of the bridge was composed of forced vibration caused by floating (or landing) and free vibration after stable levitation. The first natural frequency of the bridge could be determined using a Fourier transform of the vibration waveform. As shown in Figure 13, the maximum acceleration of full stiffness and low stiffness were 0.743 m/s^2 and 0.995 m/s^2 , respectively. It indicates that the decrease in beam height by 20 cm would increase the vertical acceleration

of the bridge by 0.252 m/s^2 , which also verifies the simulation results in Figure 4d. It could be concluded that the decrease in stiffness would increase the vibration amplitude when the bridge is subjected to the same external excitation. As shown in the spectrum diagram, the first natural frequency was 7.965 Hz at full stiffness and 7.324 Hz at low stiffness, which was reduced by 0.6 Hz . Meanwhile, the first-order natural frequency f in Figure 13 and the conversion value of natural frequency ω in Equation (9) meet the relationship: $f = \omega/L$, where L represents the span of a bridge [15]. It can be further seen that the frequency band distribution of the bridge in the range of 200 Hz was wide. It could be judged that the high frequency and local vibration of the bridge made the vibration increase in the high-frequency section. In addition, the power spectrum energy of $40\text{--}45 \text{ Hz}$ was higher, as shown in the subgraph, which indicates that the periodic irregularity caused by the local deformation of the bridge increased the vibration in the low-frequency section.

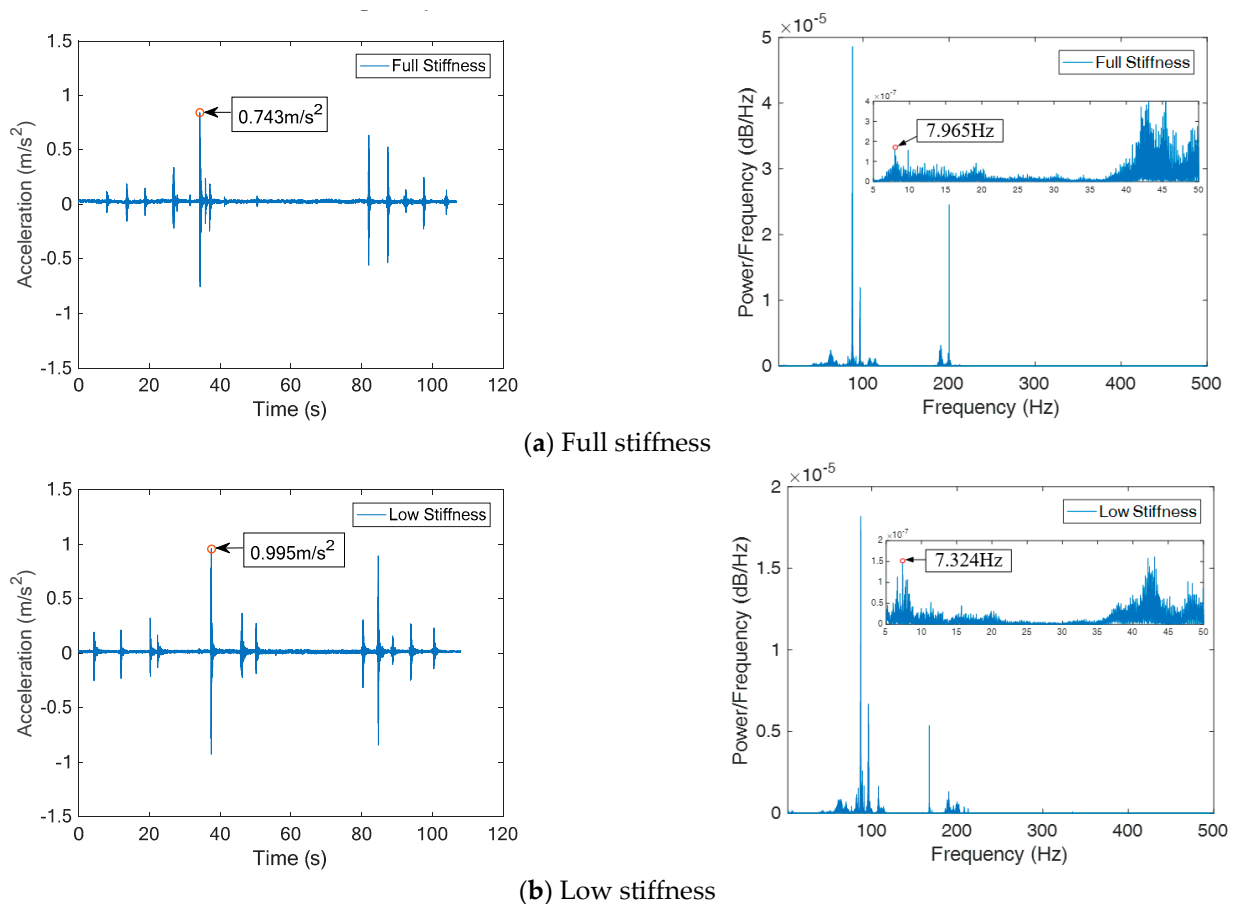


Figure 13. Effect of stiffness on the vertical acceleration of the bridge.

The effect of bridge stiffness on the vertical acceleration of suspension bogie is shown in Figure 14. The maximum vertical acceleration of full stiffness and low stiffness were 7.493 m/s^2 and 14.413 m/s^2 , respectively, which is obviously larger than the vibration amplitude of the bridge. It indicates that the vibration acceleration of suspension bogie increased by 6.92 m/s^2 when the bridge height was reduced by 20 cm , and in the $40\text{--}60 \text{ s}$ stage when the train was suspending, the vibration with low stiffness was significantly greater than that of the full stiffness. It can be seen from the spectrum diagram that the frequency band distribution in the range of 400 Hz was wider, and it had more high-frequency components than the bridge vibration spectrum, which could be regarded as the interference vibration caused by the complex components inside suspension bogie and the connected carriage. The first-order vibration frequency was 4.62 Hz at full stiffness and 5.24 Hz at low stiffness. It reflects that the first-order vibration frequency is independent of external load or stiffness, only related to the structure, size, and material of the suspension

bogie. In addition, the power frequency signal (50 Hz and its multiple frequency) generated by electromagnetic interference had higher energy.

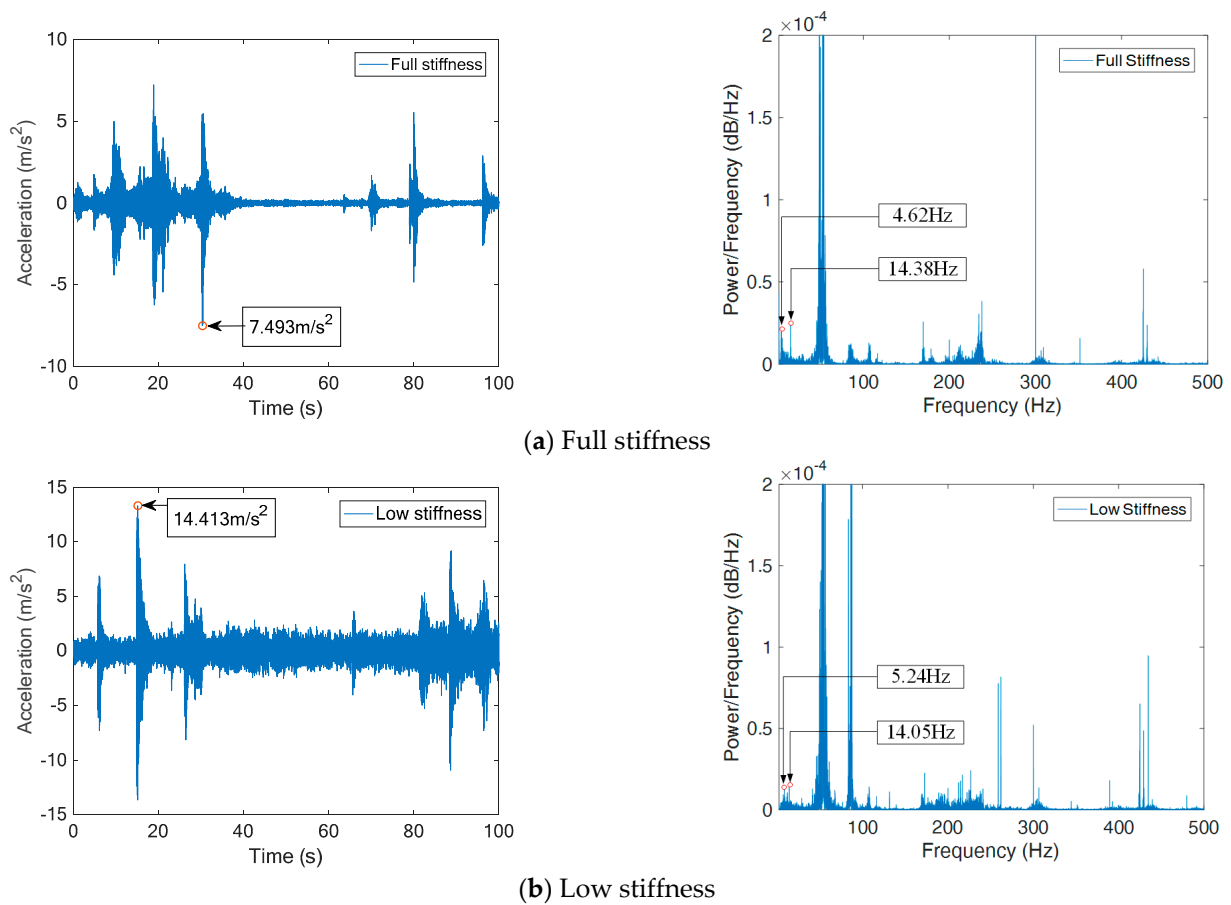


Figure 14. Effect of bridge stiffness on the vertical acceleration of the suspension bogie.

It can be observed in Figure 15 that the initial value of airgap with low stiffness was smaller, which was related to the increase in bridge deflection at low stiffness. It can be seen from Figure 2 that the larger the deflection, the smaller the relative gap between the bridge and the surface of the electromagnetic. In addition, the response speed of airgap at low stiffness was much lower than that at full stiffness, especially during 20–40 s. However, in contrast to that shown in Figure 9, an ideal levitation gap was achieved under both conditions.

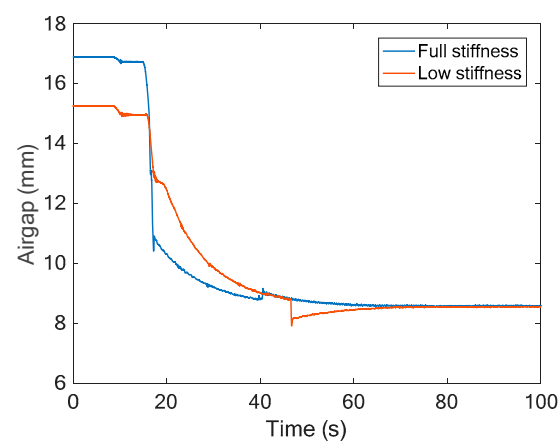


Figure 15. Effect of bridge stiffness on the airgap.

5. Conclusions

Based on the characteristics of the elastic beam, coupled maglev vehicle-bridge model based on an elastic beam was established, and the rationality of levitation operation under special conditions of overload or low bridge stiffness was verified by a numerical simulation. In addition, the dynamic performance test of a coupled vehicle-bridge system based on steel beam under different stiffness and load conditions was carried out. According to the test data, the levitation gap, vertical deflection of the bridge, vertical vibration characteristics of suspension bogie and the bridge were analyzed using the time and frequency domains, respectively. The main conclusions are as follows:

- (1) The levitation gap was significantly affected by the change of load and stiffness. When the load increased, or the stiffness decreased, the response speed of the gap became slower, and there was a steady-state error of about 1 mm under overloaded conditions;
- (2) Based on the test analysis of various conditions, the deflection of the bridge varied from 2.41 mm to 3.59 mm. At full stiffness, the load increased by 6 tons, and the deflection increased by 1.18 mm. Under no load, the beam height decreased by 20 cm, and the deflection increased by 0.94 mm;
- (3) The vertical vibration of suspension bogie and bridge increased with an increase in load or decrease in stiffness. At full stiffness, the load increased by 6 tons, and the maximum vertical acceleration of the suspension bogie and bridge increased by 7.25 m/s^2 (87.6%) and 0.401 m/s^2 (51.7%), respectively. Under no-load conditions, the beam height decreased by 20 cm, and the maximum vertical acceleration of suspension bogie and bridge increased by 6.92 m/s^2 (92.3%) and 0.252 m/s^2 (33.9%), respectively. The dynamic response of the suspension bogie changed more obviously;
- (4) The load had no effect on the first natural frequency of the bridge (about 7.1 Hz) or the suspension bogie (about 5 Hz). However, the stiffness had little influence on the first natural frequency of the bridge, and the low stiffness reduced by 0.6 Hz than the full stiffness and had no effect on the suspension bogie;
- (5) The frequency band of bridge vibration was in the range of 200 Hz, and that of suspension bogie was in the range of 400 Hz. The vertical vibration of the suspension bogie had more high-frequency components. In addition to the first-order vibration frequency, other frequencies with high energy were mostly caused by forced vibration. However, electromagnetic interference was more serious at 50 Hz and multiple frequencies (power frequency signal);
- (6) The time-domain law above was consistent with the simulation result, which verifies the reliability of the system model. In addition, the test results could be used as a reference for the design of rail transit coupling systems. In the future, new levitation control algorithms will be applied to the field test to evaluate the dynamic performance under the above conditions so as to further overcome the problems of system stability degradation caused by stiffness reduction or load increase.

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