Stability Analysis and Field Test of High-Speed Maglev Vehicle-Guideway System

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ABSTRACT

Track irregularities are a major excitation source in maglev transportation systems, and controlling these irregularities is key to ensuring long-term operational comfort. Variations in train speed alter the excitation frequency induced by track irregularities, often leading to amplified vibrations within specific speed ranges during variable-speed operation. This phenomenon negatively impacts ride comfort. This study conducted field tests on the stability of a high-speed maglev system. We investigate the vibration response characteristics of a high-speed maglev train during variable-speed operation and analyzed the stability trends of the system. A high-speed maglev vehicle-guideway coupled vibration model was developed based on parameters from the Shanghai Maglev Demonstration Line. The study investigated the dynamic behavior of key indicators, including carriage acceleration, suspension frame acceleration, and air gap, during acceleration phase, identifying the speed ranges in which vibration amplification occurs. Furthermore, the effects of key track irregularity parameters were examined by modifying the wavelength and amplitude of irregularities. The study identified the critical wavelengths that significantly influence dynamic responses under variable-speed conditions. Based on the findings, we propose the wavelength range and amplitude thresholds that should be closely monitored and controlled in acceleration zones. This research provides a theoretical basis for managing track irregularities in variable-speed sections and offers guidance for maintaining the long-term ride comfort of maglev transportation systems.

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INTRODUCTION

As a new type of rail transportation, maglev is widely considered to be an important development direction for future rail transportation. Among various types, the Electromagnetic Suspension (EMS) maglev train, which operates based on the principle of electromagnetic attraction, has become the mainstream in current maglev system development due to its technological maturity and wide application. However, the suspension gap of EMS-type maglev train maintained by electromagnetic force is typically only 10 mm, which is extremely sensitive to the change of track geometry. Therefore, the track irregularities have become one of the key factors restricting the stability of its operation and speeding ability.

A great deal of research has been conducted on the effects of track irregularities and their impact on the dynamic response of maglev systems. Shi et al. [1] carried out field measurements to obtain the power spectral density (PSD) of track irregularities along a high-speed maglev line. Liang et al. [2] derived the irregularity spectrum based on structural construction parameters of the maglev transportation line. Zhang et al. [3] measured the PSD of a low-speed maglev line and fitted a PSD function. Gao et al. [4] proposed a vision-based chord offset method for track profile measurement and experimentally validated its accuracy. Li et al. [5] and Zong et al. [6] applied the chord offset method to evaluate the PSD of medium to low speed maglev tracks, and analyzed the spatial distribution characteristics of irregularities. Han et al. [7] investigated the sensitivity of high-speed maglev vehicles to track irregularities of different wavelengths under constant-speed conditions using a coupled vehicle–guideway simulation model. Zhao et al. [8] and Shi et al. [9] studied the dynamic response of high-speed maglev systems under irregularity excitation based on derived PSD models. Xu et al. [10] analyzed the influence of track irregularity parameters on the dynamics of an EMS-type maglev system, and proposed the need to avoid short-wavelength irregularities at 600 km/h operation. Yu et al. [11] examined the dynamic response of medium-speed maglev trains under stochastic track irregularities, demonstrating that a flux-feedback-based PID controller can effectively maintain levitation gap stability. While these studies have improved a lot for understanding the influence of track irregularities on maglev systems, most studies rely on theoretical spectra or measured data within the 1–100 m wavelength range, which may limit their applicability to high-speed operating situation. Moreover, existing research predominantly focuses on constant-speed conditions, with limited attention given to the dynamic behavior of the system during acceleration.

In this study, field tests are conducted on the Shanghai high-speed maglev demonstration line to obtain representative samples of track irregularities and investigate the trends in dynamic responses of key components: such as the car body, suspension frame, and electromagnets during acceleration. Then, a high-speed maglev vehicle-guideway coupled vibration model considering the effects of track irregularities is established. The model was used to analyze the influence of irregularities with different wavelengths on system responses and to identify the wavelength ranges that should be focused for control in different speed. The findings of this study provide theoretical guidance and engineering references for improving track quality and operational stability in high-speed maglev systems.

TRACK IRREGULARITIES AND STABILITY TESTING OF HIGH-SPEED MAGLEV SYSTEM

This study conducts a test of track irregularities and system stability for high-speed maglev system, and analyze the dynamic stability of high-speed maglev vehicles under acceleration operating conditions.

Layout of Measurement Points

The vehicle measurement points are arranged as shown in Figure 1. Lateral and vertical acceleration sensors are installed on the car body. Both lateral and vertical acceleration sensors are arranged on the suspension frame. At the levitation and guidance electromagnets, sensors are placed to measure the levitation gap and vertical acceleration.

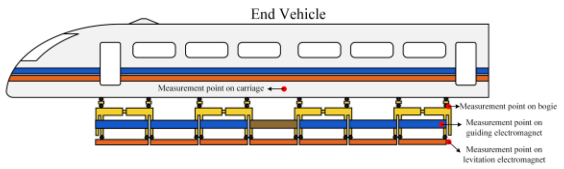


Figure 1. Layout of measurement points

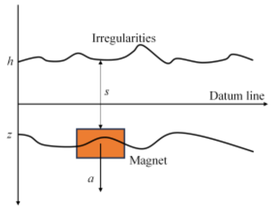


Figure 2. Inertial Reference Method

Track Irregularities Test

The principle of inertial reference method is shown in Figure 2. Measuring the acceleration of the reference body and the distance between the reference body and the object to be measured, obtaining the trajectory of the reference body through the acceleration integral and making a difference between the two to obtain the data of the object to be measured, and the formula of the inertial reference method is shown in Equation (1):

$$s_{irr} = \iint \ddot{u} \mathrm{d}t - h \tag{1}$$

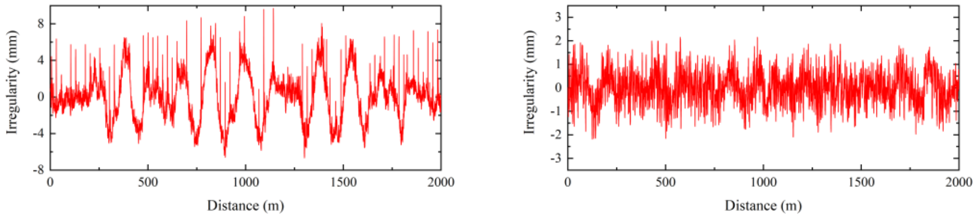
where u is the electromagnet acceleration, t is time, h represents the levitation gap, and s_{irr} is the amplitude of the track irregularity.

The measured results of track irregularities are shown in Figure 3. The stator plane irregularities exhibit more pronounced low-frequency characteristics, whereas the low-frequency features of the guidance plane irregularities are relatively weaker.

A fitting equation commonly used in the field of track irregularities testing is used, as shown in Equation (2):

$$S(f) = \frac{A\left(f^2 + Bf + C\right)}{f^4 + Df^3 + Ef^2 + Ff + G} \tag{2}$$

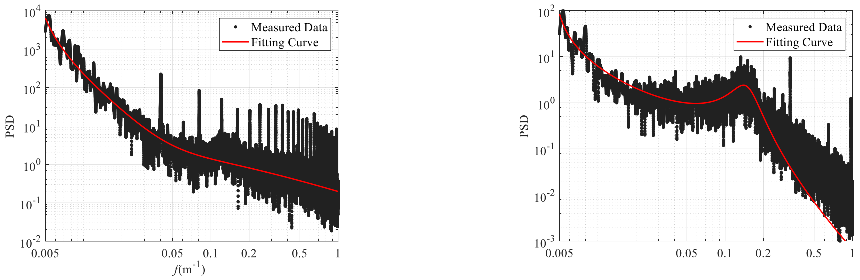
where S_{irr} represents the PSD of the track irregularity, f is the spatial frequency in units of m^{-1}, and the parameters A-F are obtained by fitting the test results.



(a) Stator Plane (b) Guidance Plane

Figure 3. Test Results of Track Irregularities

The fitting results of the track irregularities are shown in Figure 4. The power spectrum of the stator plane irregularities exhibits prominent peaks at characteristic wavelengths such as 3.096 m and 24.768 m, and the amplitude of the long-wave irregularities are larger at the wavelength greater than 100 m. Compared with the stator plane, the guidance plane irregularities have smaller amplitudes in the high-frequency range. However, their dominant irregularities amplitudes are still concentrated in the wavelength range greater than 10 m, with local peaks observed in the 5–10 m band. The fitted parameters of the irregularity PSD are listed in TABLE I.



(a) Stator Plane (b) Guidance Plane

Figure 4. Fitting results of track irregularities

TABLE I. FITTING RESULTS

	A	B	C	D	E	F	G
Stator Plane	8.911	-0.041	0.002177	41.42	1.107	-0.00978	1.88E-05
Guidance Plane	7.46E-05	5.413	0.03526	-0.2928	0.02337	-9.82E-05	-3.23E-09

Stability Test Results

Maglev vehicles typically have a high requirement for ride comfort and gap fluctuation, the former to ensure passenger comfort during operation, and the latter to prevent rail contact and ensure operational safety. In this study, field tests are conducted during the acceleration operation to measure the acceleration of the carriage, suspension frame, electromagnets and gaps. By comprehensively evaluating both ride comfort and gap fluctuation, the overall dynamic stability of the system is assessed.

The variation curves of system ride comfort indicators with speed and time during vehicle acceleration are shown in Figure 5. Local peaks can be observed in the speed ranges of 200–250 km/h and 275–325 km/h. The RMS of acceleration for the suspension frame, electromagnets, and gaps fluctuations are presented in Figure 6. Vertical dynamic responses show noticeable fluctuations within the

200–250 km/h and 275–325 km/h ranges, while lateral dynamic responses additionally exhibit local peaks in the 50–100 km/h range. These results correspond to the locations of local peaks in the carriage ride comfort curve, indicating that the vehicle exhibits higher sensitivity to track irregularity excitations in these speed ranges.

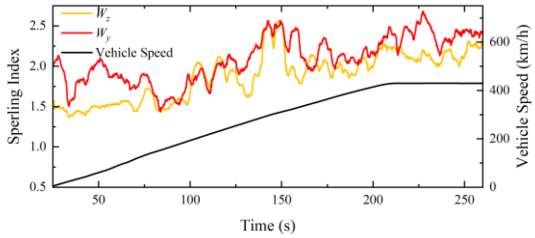
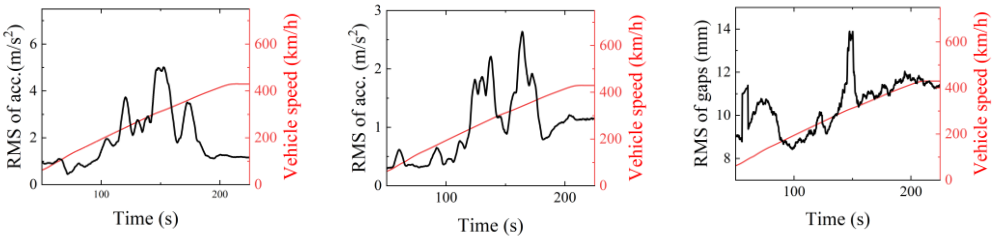
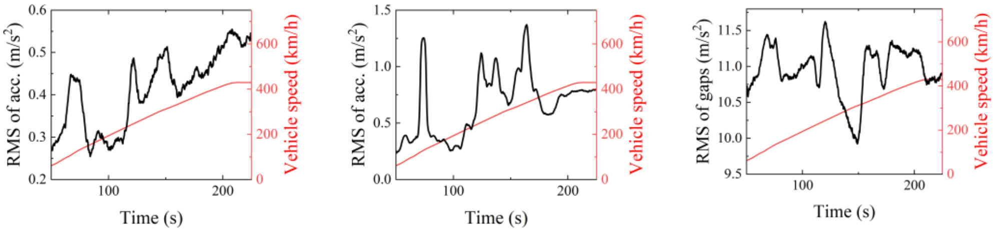


Figure 5. Sperling index during acceleration



(a) Carriage, vertical (b) Bogie, vertical (c) Magnet, vertical

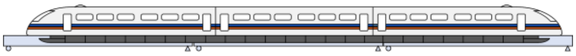


(d) Carriage, lateral (e) Bogie, lateral (f) Magnet, lateral

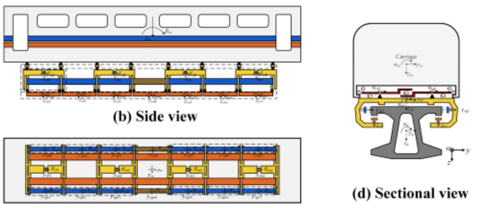
Figure 6. Variation of vehicle dynamic response RMS with speed

INFLUENCE OF TRACK IRREGULARITIES IN DIFFERENT FREQUENCY BANDS ON HIGH-SPEED MAGLEV SYSTEM

Coupled Vibration Model of High-speed Maglev Vehicle-guideway system



(a) Overall side view



(b) Side view

(c) Vertical view

(d) Sectional view

Figure 7 Maglev vehicle-guideway coupled vibration model

A vehicle-guideway coupled model was established based on the structural characteristics of the Shanghai high-speed maglev system, as shown in Figure 7.

The maglev transportation system can be divided into two subsystems: vehicle subsystem and guideway subsystem. The vehicle is modeled using multi-body dynamics, while the guideway is modeled using the finite element method. These two subsystems are coupled through electromagnetic interaction model and control algorithm.

The coupled dynamic equations for the high-speed maglev vehicle-guideway system are given in Equation (3):

$$\begin{bmatrix} M_v & \\ & M_g \end{bmatrix}\begin{bmatrix} \ddot{u}_v \\ \ddot{u}_g \end{bmatrix}+\begin{bmatrix} C_v & \\ & C_g \end{bmatrix}\begin{bmatrix} \dot{u}_v \\ \dot{u}_g \end{bmatrix}+\begin{bmatrix} K_v & \\ & K_g \end{bmatrix}\begin{bmatrix} u_v \\ u_g \end{bmatrix}=\begin{bmatrix} F_{gv} \\ F_{vg} \end{bmatrix} \tag{3}$$

where M, C and K represent the mass, damping, and stiffness matrices, respectively. $\ddot{u}$, $\dot{u}$ and u denote the acceleration, velocity, and displacement vectors. F_{gv} and F_{vg} are the electromagnetic interaction forces, where the subscripts v and g refer to the vehicle and the guideway, respectively.

F_{gv} and F_{vg} form a pair of equal and opposite electromagnetic forces, and are given by Equation (4):

$$F_{vg}=-F_{gv}=\frac{\mu_0 N^2 A}{4}\left(\frac{i}{h}\right)^2 \tag{4}$$

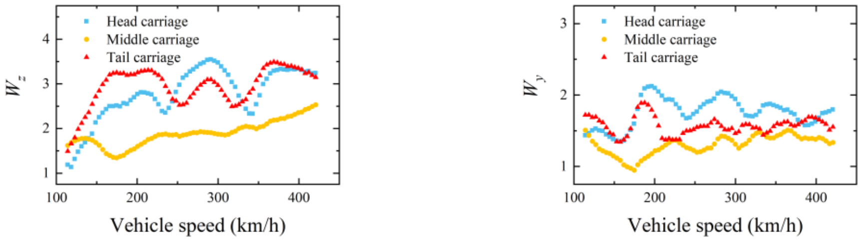
where μ_0 is the vacuum permeability, N is the number of coil turns, A is the pole area, i is current, and h is gap.

By adjusting the current based on gap, electromagnet velocity, and acceleration, the electromagnetic force can be controlled. The current control law is expressed in Equation (5):

$$\Delta i=i-i_0=k_p h+k_v \dot{u}_m+k_a \ddot{u}_m \tag{5}$$

where Δi is the variation in the control current, i_0 is the rated current, and k_p, k_v and k_a are control system parameters.

Effects of Track Irregularities in Different Wavelength Bands on High-speed Maglev Systems



(a) (b)

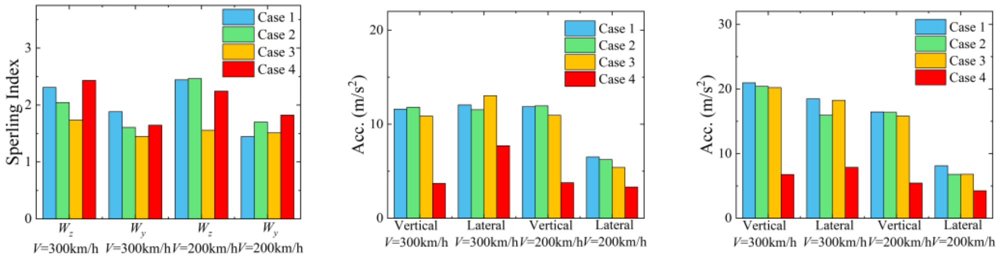
Figure 8. Variation of Sperling indices during acceleration

Figure 8 illustrates the variation of carriage Sperling indices with speed during the acceleration process. Local peaks occur at approximately 100 km/h, 200 km/h, and 300 km/h, which align well with the experimental observations, thereby validating the accuracy of the simulation. A comparison of the dynamic responses of the lead, middle, and trail carriages reveals that the lead and trail carriages exhibit significantly greater responses than the middle one. In the subsequent simulations, the dynamic response of the lead vehicle is used as a representative object for analyzing the effect of different parameters.The amplitudes of track irregularities within the 1-50 m, 50-100 m, and 100-200 m wavelength ranges were individually reduced to one-tenth of their original values. Based on these modified spectra, irregularity samples are regenerated and used as inputs for vehicle acceleration simulations. The simulation conditions are listed in TABLE II.

TABLE II. SIMULATION CONDITIONS

Case No.	Case 1	Case 2	Case 3	Case 4
Suppressed band	-	1-50 m	50-100 m	100-200 m

Figure 9 presents the system's dynamic responses under different simulation cases. As shown, suppressing track irregularities in the 50–100 m wavelength range is more beneficial for maintaining the stability of the carriage. In contrast, reducing short-wavelength irregularities in the 1–50 m range is more effective in mitigating the vibration responses of the levitation frame and electromagnets. At lower speeds, greater attention should be paid to short-wavelength irregularities, whereas at higher speeds, long-wavelength irregularities become increasingly critical. As the operating speed increases, the wavelength range of irregularities that must be addressed also expands.



(a) Carriage (b) Bogie (c) Magnet

Figure 9. Comparison of vehicle dynamic responses under varying track irregularity parameters

CONCLUSIONS

In this study, field measurements on track irregularities and operational stability of a high-speed maglev system are conducted, and the dynamic responses under variable-speed conditions are analyzed. The effects of track irregularities across different wavelength bands on vehicle dynamics at varying speeds are investigated. The main findings are as follows: (1) Field tests are conducted on the Shanghai high-speed maglev line to obtain track irregularity data, from which the power spectral characteristics are extracted. The results reveal distinct variation trends in track irregularities across different wavelength ranges. Based on the measured data, PSD functions are fitted to characterize the irregularity profile of the line. (2) A comparative analysis of dynamic responses during vehicle acceleration revealed that vibration responses were significantly amplified in the speed ranges of 200–250 km/h and 275–325 km/h, with localized peak fluctuations, which suggests that special attention should be paid to the quality of track irregularities within these speed intervals to improve operational stability. (3) Numerical simulations are conducted to assess the influence of irregularity suppression across different wavelength bands. The results indicate that irregularities in the 50-100 m range have the greatest impact on carriage dynamics, while those in the 1-50 m range predominantly affect the responses of the levitation frame and electromagnets. Targeted suppression within these bands is thus recommended to mitigate system vibrations effectively.

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REFERENCE

1. Jin Shi, Wenshan Fang, Yingjie Wang, Yang Zhao. Measurements and analysis of track irregularities on high speed maglev lines [J]. *Journal of Zhejiang University SCIENCE A*, 2014, 15(6): 385-394.
2. Xin Liang, Sansan Ding, Chao Huang, Dalian Yu. Prediction Method of Irregularity of High-speed Maglev Track Based on Normal Distribution Superposition Principle[J]. *Electric Drive for Locomotives*,2020,(06):20-24.
3.Geng Zhang, Jie Li, Zijing Yang. Estimation of Power Spectrum Density Track Irregularities of Low-speed Maglev Railway Lines[J]. *Journal of the China Railway Society*,2011,33(10):73-78.
4. Xiongjie Gao, Long Yu, Tanglong Chen. Detection of Medium and Low Speed Maglev Track Irregularity Based on MCO[J]. *Journal of the China Railway Society*, 2020,42(08):116-122.
5.Mengxue Li, Min Zhang, Weihua Ma, Shihui Luo.Study on the Power Spectrum Irregularities in Medium and Low Speed Maglev Tracks[J]. *Railway Standard Design*,2024,68(09):40-47.
6. Lingxiao Zong, Junxiong Hu, Mengchun Pan, Qi Zhang, Weihua Ma. Experimental measurement of track irregularities in EMS maglev systems using the mid-chord offset method and inverse filtering technology[J]. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2025, 239(2): 106-115.
7.Yan Han, Xiumeng Bu, Lidong Wang, Ying Luo, Kai Li. High-speed maglev train-track beam coupled system track irregularity sensitive wavelengths[J]. *Journal of vibration and shock*,2024,43(05):1-11+19.
8. Chunfa Zhao, Wanming Zhai. Maglev vehicle/guideway vertical random response and ride quality[J]. *Vehicle system dynamics*, 2002, 38(3): 185-210.
9. Jin Shi, Qingchao Wei, Yang Zhao. Analysis of dynamic response of the high-speed EMS maglev vehicle/guideway coupling system with random irregularity[J]. *Vehicle System Dynamics*, 2007, 45(12): 1077-1095.
10.Aokang Xu, Miao Li, Aibin Wang, Xianhong Shang, Weihua Ma, Shihui Luo.Study on the Influence of Track Irregularity Parameters of EMS High-speed Maglev[J]. *Railway Standard Design*,2025,69(02):36-44.
11. Peichang Yu, Mengxiao Song, Qiang Chen, Lianchun Wang, Guang He, Peng Leng. Dynamic Response Analysis of Medium‐Speed Maglev Train with Track Random Irregularities[J]. *Journal of Advanced Transportation*, 2021, 2021(1): 1668496.