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Stability Simulation and Analysis of Maglev Vehicle at Different Speed Based on UM

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Abstract: High-speed maglev train is an excellent mode of transportation to build a transportation network because of its high safety, low emission, low energy consumption, low noise and strong climbing ability. The safety, stability and comfort of high-speed maglev train are closely related to the running speed and the random track irregularity, so it is necessary to study the corresponding relationship between the running speed, the random track irregularity and the stability. In order to ensure the safety and stability of high-speed maglev train in high-speed running, a dynamic model of high-speed maglev vehicle is established by UM based on Shanghai TR08 maglev train to carry out simulation analysis of its response to various track irregularity stimulations at different speeds and study the change law of stability of maglev train at different speeds, so as to provide a useful reference for the design optimization of high-speed maglev vehicle and the irregularity control of maglev line.

Keywords: High-speed maglev train; Dynamic modeling; Simulation analysis; Irregularity spectrum; Sperling stability index

1. Introduction

Maglev train is featured with high safety, low emission, low energy consumption, low noise and strong climbing ability because of its unique characteristics of running by electromagnetic force. In recent years, maglev train has attracted wide attention and strong interest from all over the world, and is considered as a highly competitive mode of transportation in the new century. Germany has built Emsland test line and Japan has set up Miyazaki test line and Yamanashi test line. The study on maglev train technology in China started late, but developed rapidly: Shanghai Maglev Train, the first commercial demonstration line of maglev train in the world, was completed and opened to traffic in 2002, and has been operating safely since then; Changsha Maglev Express, completed in 2016, is the first medium and low speed maglev line with completely independent intellectual property right in China; in 2021, the high-temperature superconducting high-speed maglev sample train developed by Southwest Jiaotong University was successfully rolled off the production line, with an expected running speed exceeding 600 km/h. The rapid development of maglev train in China in recent years fully demonstrates the determination and strength of developing maglev transportation in China.

In September 2019, the CPC Central Committee and the State Council Issue the Program of Building National Strength in Transportation, proposing that by 2035, a "national 123 transportation circle" (one-hour commute in urban areas, two-hour travel between the cities of a conurbation, and three-hour reachability of major cities nationwide) will have been formed, with advanced, applicable, complete and controllable transportation equipment. 600 km/h high-speed maglev train is undoubtedly an extremely suitable mode of transportation to build a large-scale rapid transportation network between conurbations, and high-speed maglev train will enter a high-speed development stage. China is a big country with a vast territory, which has an urgent need for high-speed transportation. Actively promoting the research and development of high-speed maglev train technology is of great significance for improving China's transportation technology level, promoting economic development and building a socialist modern power in an all-round way.

As mentioned above, it is imperative to promote the related research of high-speed maglev train. Although the maglev train is suspended and guided by electromagnetic force, runs around the track beam, and has no direct contact with the track, there are still a lot of dynamic problems, especially in the case of high speed, such as dynamic curve passage, stability and vehicle-bridge coupling vibration. The study on these problems is related to the safety, stability and comfort of maglev train. Regardless of the type of maglev train, the study on running stability is one of core issues, and the study on running stability at high speed is the most important.

In recent years, many scholars at home and abroad have carried out a lot of researches on the dynamic modeling and simulation of high-speed maglev train, and made many achievements. Zhao et al. [1] established a dynamic model of elastic suspension frame and the models of high-speed maglev vehicle, bridge, line and controller, and analyzed some dynamic problems, including modal analysis and dynamic response of three transition curve types (sine, cosine and cyclotron) to the curve passage of maglev train. Zhou et al. [2] took TR08 maglev vehicle as prototype to establish a vertical dynamic model of maglev vehicle, and calculated response power spectrum of maglev vehicle by virtual stimulation method. Li et al. [3] obtained the real-time vibration signal of the maglev train through the running test on the track, and analyzed the vibration signal of the train body from the real domain and frequency domain by FFT and STFT algorithms, and gained the stability grade of the train in the lateral and vertical directions. Zhang [4] took CMS-3A maglev train as the research object, and used the prediction method based on recursive composite Back Propagation network to predict the fluctuation amplitude of suspension gap at this position where the train passes through the track in the future, and then evaluated the safety impact caused by track irregularity. Yang and Zheng [5] took Changsha Maglev Express as an example to introduce the principle and structure of the running mechanism of short stator maglev vehicle, and established a mechanical simulation model in SIMPACK motion; as well as analyzed and calculated the stability of maglev vehicle at different speeds by modeling and simulation method. Chen et al. [6] established a dynamic model of EMS high-speed electromagnetic suspension vehicle based on the multi-body dynamics theory, and studied the influence of train suspension system parameter and track irregularity amplitude on the dynamic performance of 600 km/h high-speed maglev vehicle. Liu et al. [7] established a virtual prototype model and track irregularity model of maglev train, simulated and analyzed its running stability under different loads and speeds, and obtained the Sperling stability index of each marshalling train under different working conditions. Yan et al. [8] firstly carried out rigid body modeling and rigid-flexible coupling modeling for a maglev vehicle, and analyzed the vertical acceleration transmission characteristics and lateral acceleration transmission characteristics of rigid body model and flexible body model at arm claw, air spring seat and vehicle body respectively by time domain and frequency domain methods. Wang et al. [9] used PID suspension control method to establish a dynamic model of maglev train; and constructed coherence function between irregularity and train body vibration according to the coherence principle. Wang and Lu [10] simulated and analyzed the stability and comfort of the vehicle after the input line irregularity stimulation by establishing a dynamic model of high-speed maglev vehicle. Through the analysis and optimization of suspension parameters of high-speed maglev vehicles, they explored the running stability and comfort of the vehicle at different speeds. Shi et al. [11] constructed a new type of maglev vehicle dynamic model and found that the dynamic interaction between the redesigned suspension bogie structure and track beam is small through computer simulation analysis and comparison of track dynamic model established by new and old bogies, indicating that the working environment of electromagnets in the new type of maglev train has been improved. Talukdar and Talukdar [12] summarized a method of modeling and simulating maglev vehicle-guide track by using SIMULINK software, studied the influence of vehicle speed and track irregularity on vehicle performance, analyzed the dynamic response of vehicle-guide track, and optimized suspension parameters. Based on Transrapid system, Zhao and Zhai [13] developed a 10-degree-of-freedom model of maglev vehicle running at constant speed on three types of guide tracks; discussed the construction of track random irregularity, simulated based on this, obtained the response of maglev train and calculated the stability; used direct time integration method and discrete fast Fourier transform (DFFT) to study the random response of maglev vehicle-track system, and obtained the resonance frequency of vehicle body acceleration.

Based on the above literature, most of researches focus on the nonlinear model of maglev train-bridge coupling system below 400 km/h speed level. The vibration of the coupled system under resonant velocity is studied by means of numerical and modeling simulation methods. The influence of parameters in the system, such as vertical stiffness and damping of primary and secondary systems, suspension gap and track irregularity wavelength on the vibration of the system is observed, and various optimization schemes are put forward. The speed level of the above researches is low, and most of the factors considered are single. For example, only the influence of track irregularity and vehicle speed on vehicle dynamic performance is considered. There are few studies on the stability and sensitive working conditions of maglev train at high speed above 500 km/h, which brings troubles to the high speed of maglev train. The development of high-speed maglev in China must solve this problem. Therefore, it is necessary to establish a simulation model to explore the response of maglev train to various working conditions and the change law of stability index at high speed.

This paper takes TR08 high-speed maglev train of Shanghai Maglev Demonstration Line in China as the prototype, establishes a dynamic model of high-speed maglev vehicle by using multi-body dynamics software Universal Mechanism (UM). According to the actual or near-actual parameters, the electromagnetic force control model, flexible track beam, track irregularity stimulation and other parameters are set up, and the dynamic simulation analysis of multiple working conditions is carried out in UM. The response of high-speed maglev train under different stimulation is obtained, and the change law of maglev train's stability at high speed is analyzed. MATLAB is used to write a script that converts acceleration into Sperling stability index, and obtain various data that can reflect the running status of high-speed maglev train, and carry out drawing processing. Then Excel is used to collect all kinds of data indexes and draw line charts to make them intuitive, and analyze the change law of running status of maglev train.

2. Basic Theory of Stability of High-speed Maglev Train

2.1 Introduction of Irregularity Types of Maglev Track

In the straight line or curve section, the deviation of the left and right induction tracks bearing the vertical load of maglev vehicle from the ideal straight track or the designed track curve in the height and left and right directions is called track irregularity.

Track irregularity is generally described as four types of irregularity [14]:

(1) Vertical irregularity of track

The mean value Z_v of the left and right track surface irregularity indicates the height deviation of the nominal center of the center line of the vertical support point of the left and right track, which is the main reason for causing vertical vibration of the train, so the train will have ups and downs and nodding vibration.

$$Z_v = \frac{Z_1 + Z_2}{2} \tag{1}$$

For maglev vehicle, Z_1 and Z_2 are the surface heights of left and right magnetic tracks.

(2) Horizontal irregularity of track

The angle formed by the connecting line between the left and right magnetic track surfaces and the horizontal plane or design mass changes into horizontal irregularity that is an important cause of shaking head and rolling of maglev train.

$$\theta_c = \frac{Z_1 - Z_2}{2b} \tag{2}$$

where, b is half of the distance between left and right magnetic tracks.

(3) Track direction irregularity

Track direction irregularity is the lateral displacement of the center line of the left and right magnetic guide sides relative to the design mass. Direction irregularity is an important cause of shaking head and rolling of track vehicle.

$$y_a = \frac{y_1 + y_2}{2} \tag{3}$$

(4) Gauge irregularity

Gauge irregularity refers to the deviation of gauge of the left and right tracks along the track length direction, and its value is expressed by the difference between the actual gauge and the nominal gauge. Gauge irregularity will bring about change in balance position and guiding force in the running of maglev vehicle.

$$y_g = y_2 - y_1 - g \tag{4}$$

where, g is nominal gauge.

2.2 Calculation Method of Sperling Stability Index

According to GBT 5599-2019 Code for Dynamic Performance Evaluation and Test Appraisal of Rolling Stock [15], the running stability of maglev train is the main basis for evaluating passengers' comfort feeling of vibration during maglev running, and the evaluation index is the fatigue degree felt by passengers. Sperling stability index W is divided into vertical and lateral stability indexes based on the vibration acceleration measurement in the corresponding direction of the vehicle body.

The evaluation method of stability index W is as follows

(1) Measure the vibration acceleration in the corresponding direction of the vehicle body, and the standard

measurement time is 5 S;

(2) Analyze spectrum of acceleration [16];

(3) Calculate stability index component W_i at the frequency f_i, as shown in Eq. (5).

$$W_i = 3.57 \sqrt[10]{\frac{A_i^3}{f_i} F(f_i)} \tag{5}$$

where,

i is 1, 2, 3...

A_i is vibration acceleration (m/s^2);

f_i is vibration frequency (Hz), and the value range is $0.5\text{Hz} \le f_i \le 40\text{Hz}$;

$F(f_i)$ is frequency correction coefficient, as shown in Table 1.

Table 1. Frequency domain correction coefficients

Vertical vibration		Lateral vibration	
f/Hz	*F(f)*	*f/Hz*	*F(f)*
0.5≤*f*<5.9	0.325*f*²	0.5≤*f*<5.4	0.8 *f*²
5.9≤*f*<20	400/*f*²	5.4≤*f*<26	650/*f*^2
20≤*f*<40	1	26≤*f*<40	1

(4) Calculation of stability index

$$X_1 = \sqrt[10]{w_1^{10} + w_2^{10} + \cdots + w_n^{10}} = \sqrt[10]{\sum_{i=1}^{n} w_i^{10}} \tag{6}$$

where, i is 1, 2, 3…;

W_i is stability index component when the frequency is f_i.

In this paper, the acceleration response can be derived in UM and recorded in txt format. Import data function of MATLAB is used to extract one-dimensional array of time and one-dimensional array of acceleration from the acceleration file, and DFFT is adopted to get the frequency domain diagram of acceleration, and then the stability index W can be obtained by weighted calculation.

3. Establishment of Dynamic Model of High-speed Maglev Train System

3.1 Vehicle Model

Figure 1 shows a model of high-speed maglev train established in UM, which consists of a train body and six suspension shelf systems. There is a frame, two suspension electromagnets and two guide electromagnets in each suspension shelf system. Each electromagnet has four acceleration sensors. There is primary suspension before the electromagnet and the frame, and secondary suspension between the train body and the frame. The model has a total of 114 degrees of freedom.

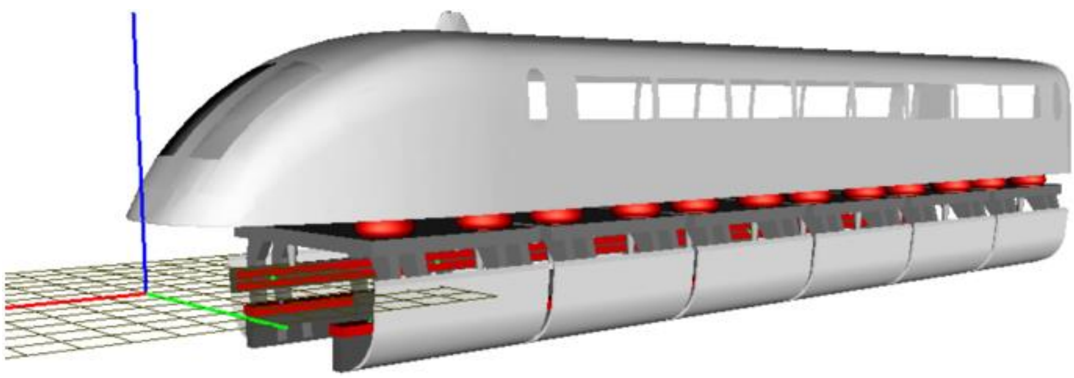

Figure 1. Dynamic model of high-speed maglev train

The dynamic parameters of the model are shown in Table 2.

Table 2. Dynamic parameters of dynamic model of high-speed maglev train

Parameter	Symbol	Value
Body mass / kg	m_carbody	15000
Mass of suspension frame / kg	m_frame	1000
Mass of suspension and guide electromagnet / kg	m_magnet	600
Matrix of moment of inertia of train body / $(kg \cdot m^2)$		Diag (5e4,3e5,3e5)
Matrix of moment of inertia of suspension frame		diag(1000,1000,1000)
Matrix of moment of inertia of suspension and guide electromagnets		Diag (20,600,600)
Quantity of suspension frame	n_bogies	6
Vertical stiffness of air spring / $(N \cdot m^{-1})$	kz_2	2.00E+05
Lateral and longitudinal stiffness of air spring / $(N \cdot m^{-1})$	kxy_2	1.00E+04
Vertical damping of air spring / $((N \cdot s \cdot m^{-1})$	cz_2	3000
Lateral and longitudinal damping of air spring / $((N \cdot s \cdot m^{-1})$	cxy_2	2000
Pre-pressure of spring / N	fz2	6131.25
Initial guiding force / N	fy0	5000
Initial suspension force / kN	fz0	14.46975

3.2 Model of Suspension Frame

In Figure 2, each suspension frame has 4 air springs, 2 suspension electromagnets and 2 guide electromagnets. The connection relationship between the suspension frame and the parts is as follows: Relative to the frame, the suspension electromagnet has the freedom of translation along X and Z axes and rotation along Y axis, and stiffness matrices CX=5e6, CZ=5e6, CAY=1e5, DX=5e4, DZ=5e4, DAY=1e3 are arranged at the connection points; Relative to the frame, the guide electromagnet has the degree of freedom of translation along X and Y axes and rotation around Z axis, and stiffness matrices CX=5e6, CY=5e6, CAZ=1e5, DX=5e4, DY=5e4 and DAZ=1e3 are arranged at the connection points; The upper vertex of the air spring is connected with the train body, and the lower vertex is connected with the frame. The sum of the initial pre-pressures of all springs is equal to the gravity of the train body.

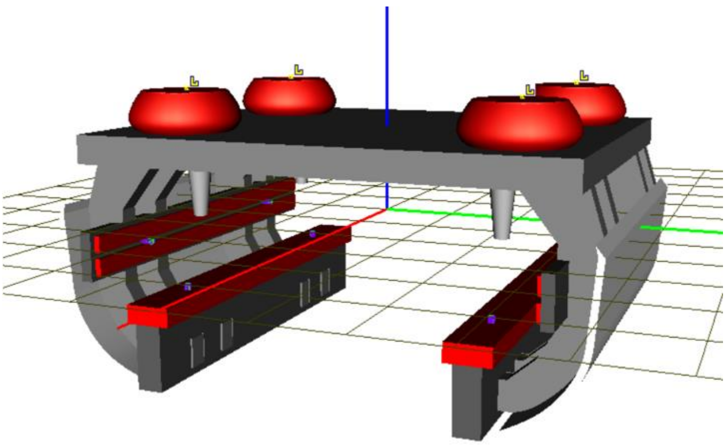

Figure 2. Model of suspension frame

Due to the single electromagnet control model, for the convenience of simulation, two concentrated forces are uniformly applied to the front and rear of each suspension electromagnet and guide electromagnet in the maglev bogie model (see blue dots on the red faces of the suspension electromagnet and guide electromagnet in Figure 2) to replace electromagnetic forces. At the same time, two gap sensors are set at the position where the forces are applied to detect the distance between the electromagnet and the corresponding track surface, so as to feedback and adjust the electromagnetic force, and realize the control of suspension force and guiding force. The initial value of suspension electromagnetic force is fz0, and that of guiding force is fy0.

4. Dynamic Response Result and Stability Analysis of High-speed Maglev Train System

Dynamic simulation is carried out by UM, and the simulation data of irregularity type stimulation has been processed by MATLAB script, and the related simulation results are as follows.

4.1 Long Wave

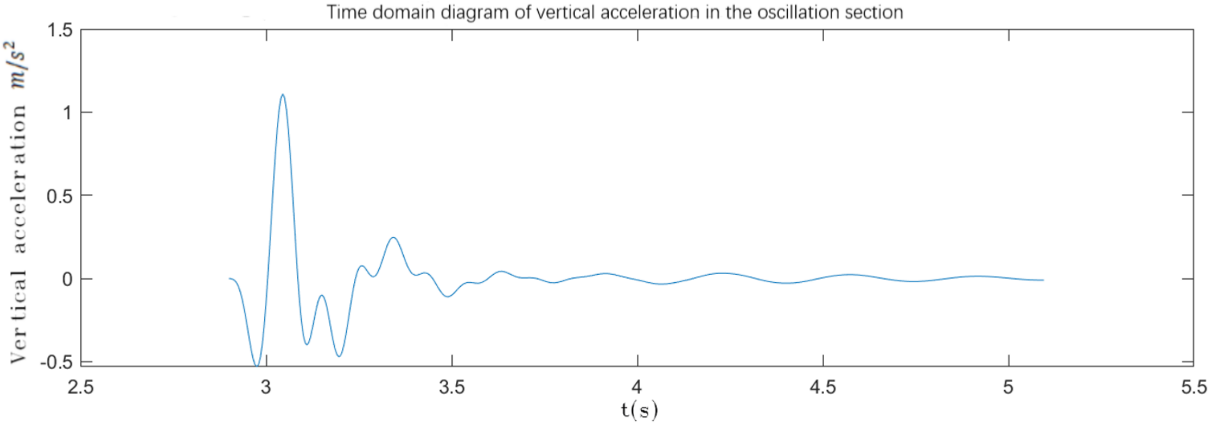

Figure 3. Vertical acceleration response of train body at the speed of 600 km/h under long wave 1 working condition

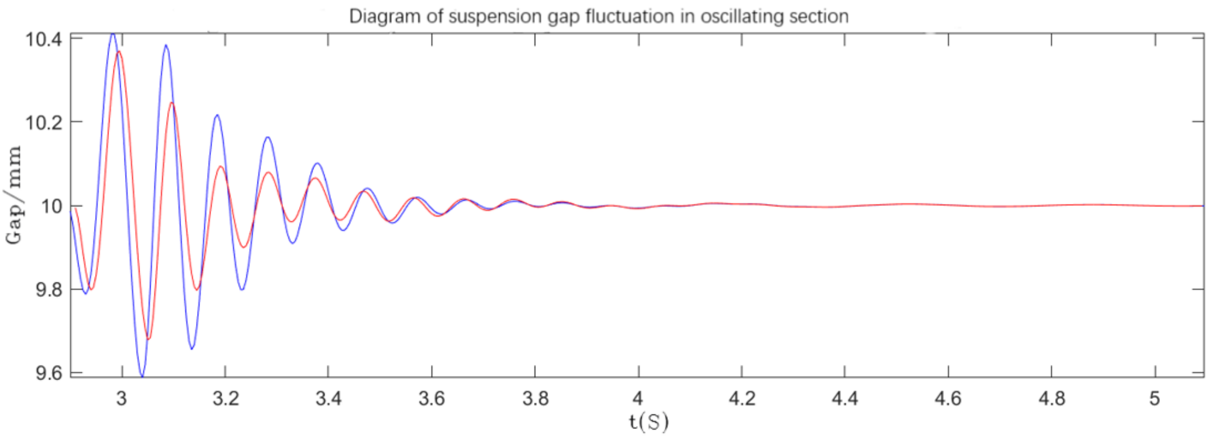

Figure 4. Suspension clearance response at the speed of 600 km/h under long wave working condition 1 (suspension point in front of blue line and suspension point behind red line)

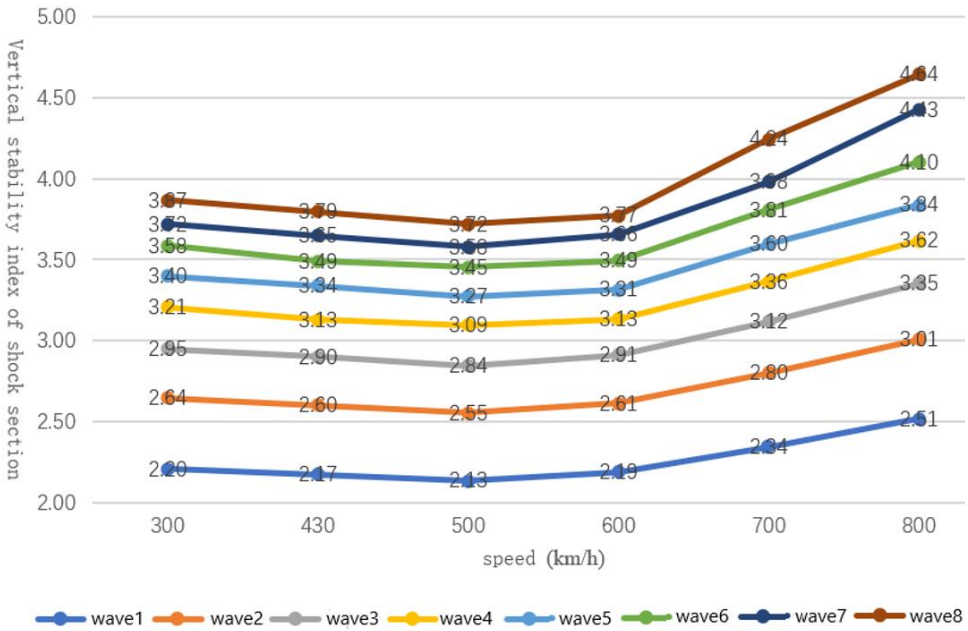

Figure 5. Vertical stability index of vibration section under long wave 1-long wave 8 working conditions

Considering that the deflection of the track beam will change when it bears its own gravity and the gravity of maglev train, a half-sine wave protruding downward is constructed with a span length of 24 m and an amplitude of 1 mm according to the deformation characteristics of simply supported beam under load. Long wave working conditions 1-8 are amplified by 1-8 times of the half-sine wave stimulation respectively, and the simulation results are shown in Figures 3-5.

As shown in Figure 5, under the stimulation of long wave 1 irregularity waveform, with the increase of magnification times of irregularity (long wave 1-long wave 8 working conditions correspond to 1-8 magnification times), the stability index at the same speed also increases. Under the same working condition, the running speed increases from 300 km/h to 500 km/h, and the stability index decreases slightly; When the running speed increases from 500 km/h to 800 km/h, the stability index increases accordingly.

4.2 Short Wave

The irregularity of short wave is mainly caused by the angle deviation of stator core system, which can be divided into the following three working conditions:

(1) Short wave working condition 1: the standard length is 1,032 mm, the height changes by 0.75 mm, each sawtooth period contains two sections of 1,032 mm, the NGK is 1.5 mm, and the short wave difference is 0.75 mm.

(2) Short wave working condition 2: the standard length is 1,032 mm, the height changes by 0.35 mm, each sawtooth period contains four sections of 1,032 mm, the NGK is 1.5 mm, and the short wave difference is 1.1 mm.

(3) Short wave working condition 3: the standard length is 1,032 mm, the height changes by 0.25 mm, each sawtooth period contains six sections of 1,032 mm, the NGK is 1.5 mm, and the short wave difference is 1.5 mm.

The simulation results of short wave 1 working condition are shown in Figures 6-8:

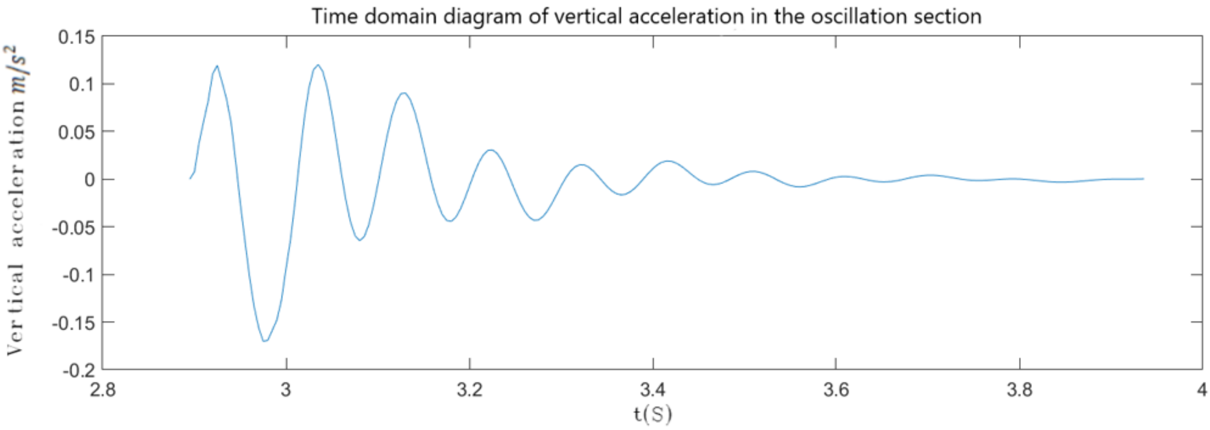

Figure 6. Vertical acceleration response of train body at the speed of 600 km/h under short wave 1 working condition

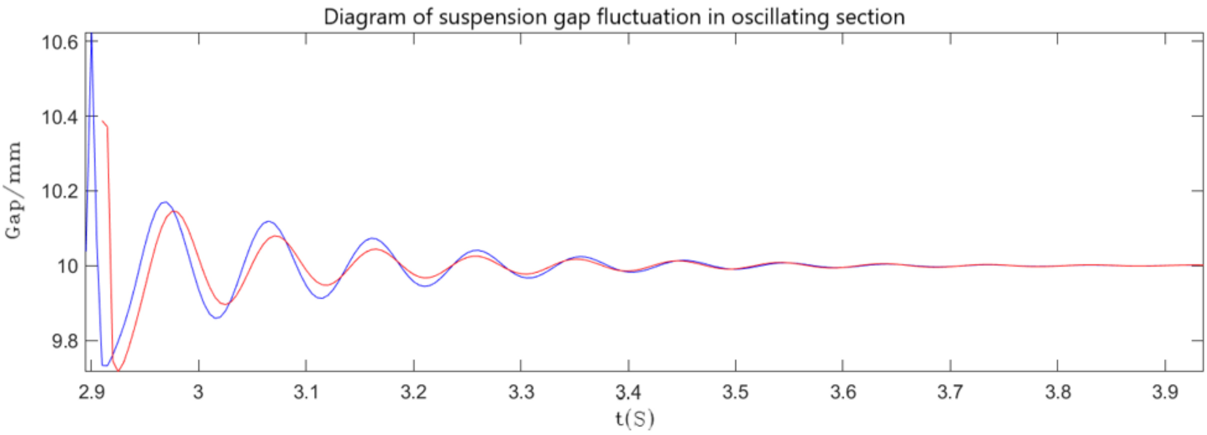

Figure 7. Suspension clearance response at the speed of 600 km/h under short wave 1 working condition (suspension point in front of blue line and suspension point behind red line)

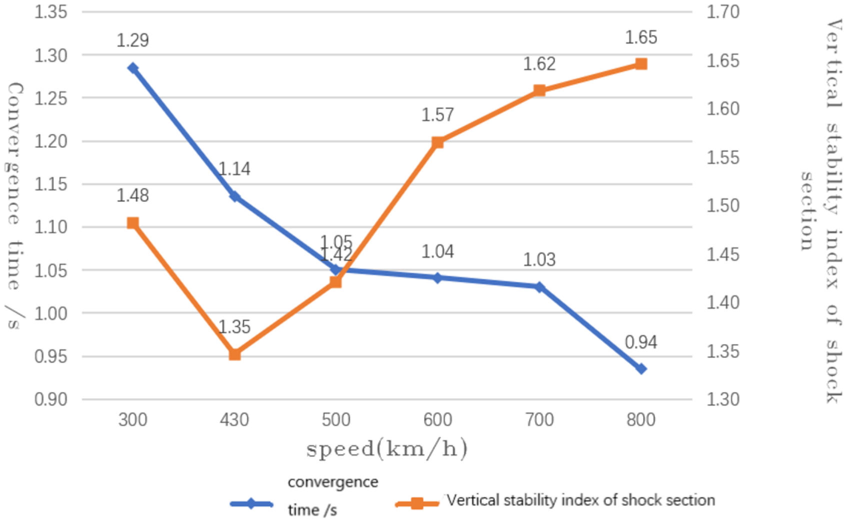

Figure 8. Convergence time of short wave 1 and vertical stability index of vibration section

It can be seen from Figure 8 that under the stimulation of short wave 1 irregularity waveform, the running speed of maglev train increases from 300 km/h to 430 km/h, and the stability index decreases slightly; When the running speed increases from 430 km/h to 800 km/h, the stability index increases accordingly. The convergence time decreases with the increase of speed.

The simulation results of short wave 2 working condition are shown in Figures 9-11:

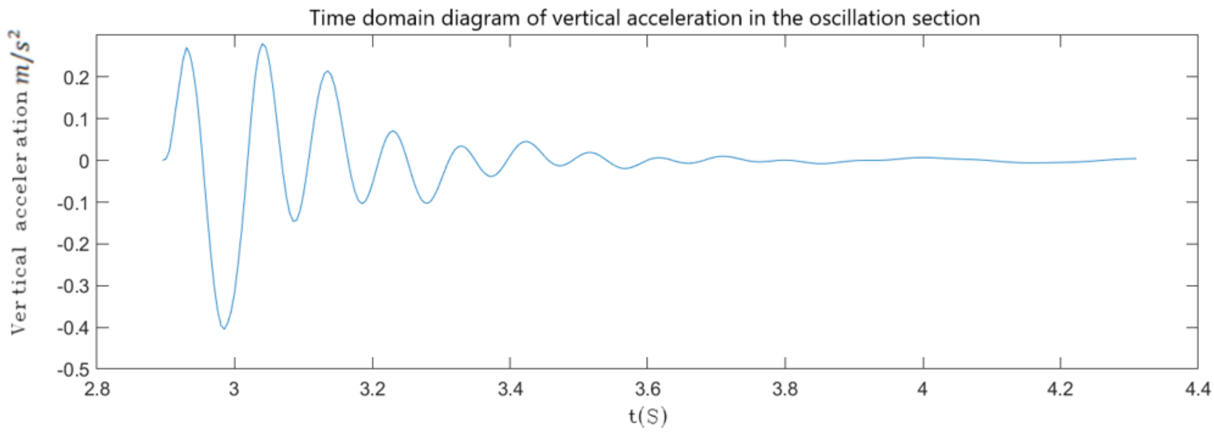

Figure 9. Vertical acceleration response of train body at the speed of 600 km/h under short wave 2 working condition

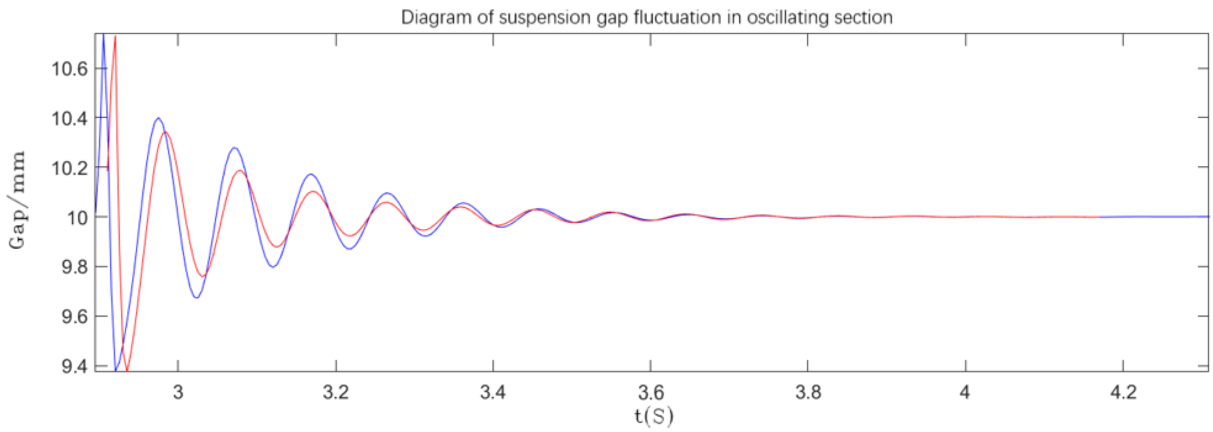

Figure 10. Suspension clearance response at the speed of 600 km/h under short wave 2 working condition (suspension point in front of blue line and suspension point behind red line)

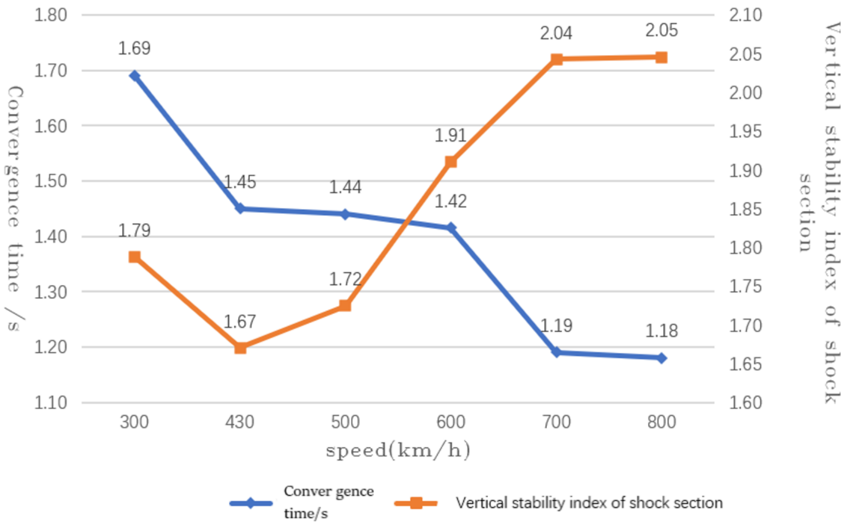

Figure 11. Convergence time of short wave 2 and vertical stability index of vibration section

As can be seen from Figure 11, under the stimulation of short wave 2 irregularity waveform, the running speed of maglev train increases from 300 km/h to 430 km/h, and the stability index decreases slightly; When the running speed increases from 430 km/h to 800 km/h, the stability index increases accordingly. The convergence time decreases with the increase of speed.

The simulation results of short wave 3 working condition are shown in Figures 12-14:

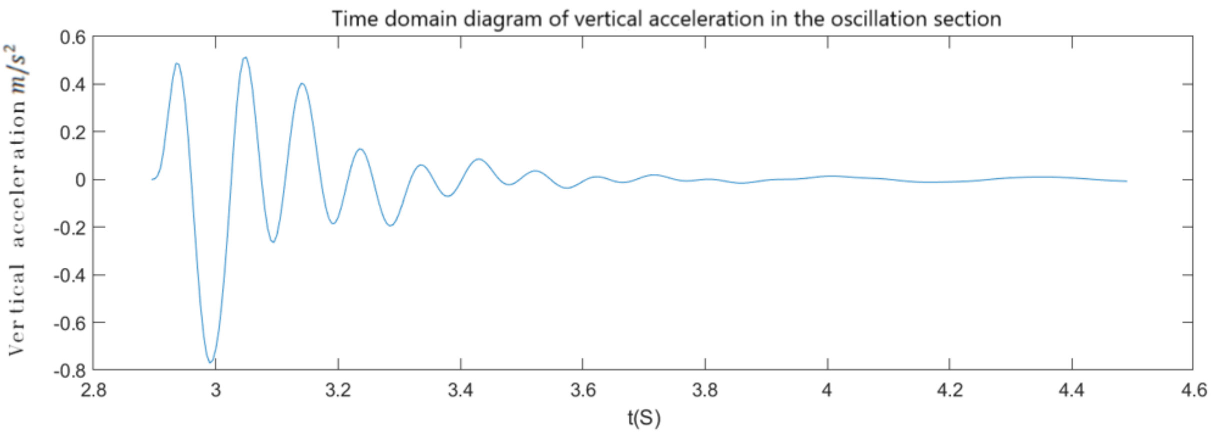

Figure 12. Vertical acceleration response of train body at the speed of 600 km/h under short wave 3 working condition

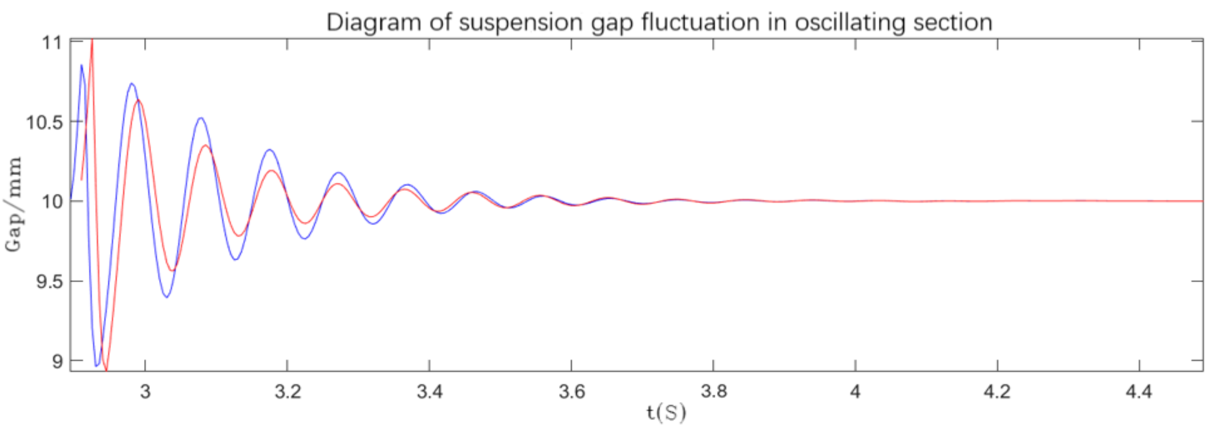

Figure 13. Suspension clearance response at the speed of 600 km/h under short wave 3 working condition (suspension point in front of blue line and suspension point behind red line)

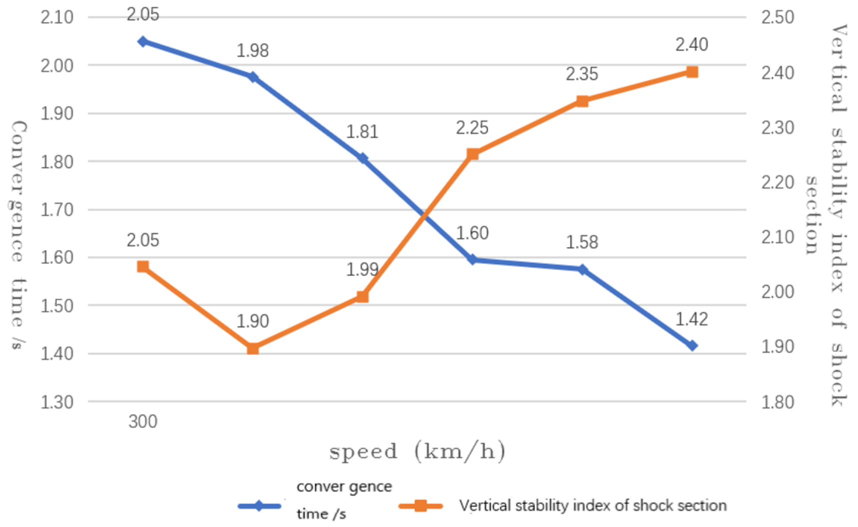

Figure 14. Convergence time of short wave 3 and vertical stability index of vibration section

As can be seen from Figure 14, under the stimulation of short wave 3 irregularity waveform, the running speed of maglev train increases from 300 km/h to 430 km/h, and the stability index decreases slightly; When the running speed increases from 430 km/h to 800 km/h, the stability index increases accordingly. The convergence time decreases with the increase of speed.

5. Conclusion

In this paper, the TR08 high-speed maglev train of Shanghai Maglev Track Demonstration Line is taken as the prototype, and the dynamic model of high-speed maglev train is established by UM to carry out simulation research work under the stimulation of long wave irregularity and short wave irregularity. The main research conclusions are as follows: No matter under what type of suspension surface irregularity stimulation, the train's stability index will first decrease and then increase with the increase of speed, mainly because: 1. The target suspension gap changes with the increase of speed. It is speculated that the target suspension clearance is closely related to the vertical stability index. 2. The faster the speed is, the less time it takes to pass through the uneven road section, and the less time it takes for the train to be stimulated by irregularity, but the sum of energy of irregularity stimulation per unit time is greater. The vertical stability index is related to the stimulation duration and total energy of irregularity stimulation in unit time. Both is similar to inversely proportional relationship under the same working condition, which leads to the possible existence of an optimal speed value, making the vertical stability index minimum. Thus, under single irregularity stimulation, the image of running speed and vertical stability may be similar to a quadratic function with a lowest point. At the same time, with the increase of running speed, the shorter the time for the train to recover from irregularity stimulation, the greater the fluctuation of suspension clearance will be larger as a whole. In the whole irregularity spectrum, single irregularity stimulation can be regarded as a unit pulse function. The faster the running speed is, the shorter the duration of the pulse function is and the larger the pulse amplitude is, then the larger the peak value of train response will be. In the future work, study will focus on the multi-body dynamics of rigid-flexible track beam of high-speed maglev train. Flexible track beam is not used in the above simulation analysis. This paper thinks that establishing a more perfect maglev train-track beam coupling model can better study the change law of stability index.

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Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] C. F. Zhao, W. M. Zhai, and X. Y. Ye, "Dynamic modeling and simulation of high-speed maglev vehicle and its elastic levitation chassis," *J. Syst. Simul.*, vol. 20, no. 2, pp. 5718-5721, 2008.

[2] J. S. Zhou, D. G. Li, G. Shen, L. H. Ren, and X. W. Zhang, "Pseudo-excitation analysis method of riding quality for maglev vehicle," *J. Traffic Transport. Eng*., vol. 8, no. 1, pp. 5-9, 2008. http://dx.chinadoi.cn/10.3321/j.issn:1671-1637.2008.01.002.

[3] W. L. Li, T. X. Chen, R. X. Hu, and X. Li, "Study on running stability of maglev train," *Mechanical Sci. Technol. Aerospace Eng*., vol. 38, no. 5, pp. 677-683, 2019. http://dx.chinadoi.cn/10.13433/j.cnki.1003-8728.20180238.

[4] Y. T. Zhang, "Research on comprehensive monitoring of state and prediction of track irregularities for medium-low speed maglev trains," Master Dissertation, National University of Defense Technology, China, 2008.

[5] Y. Yang and T. T. Zheng, "Speed-up run stationarity of short stator maglev train," *Electric Locomotives Mass Transit Vehicles*, vol. 45, no. 1, pp. 20-25, 2022. http://dx.chinadoi.cn/10.16212/j.cnki.1672-1187.2022.01.005.

[6] Z. X. Chen, H. Xu, Z. J. Li, and Y. Li, "Research on secondary suspension parameters and track irregularity amplitude of high-speed maglev train," *Railway Standard Design*, vol. 65, no. 7, pp. 65-69, 2021. http://dx.chinadoi.cn/10.13238/j.issn.1004-2954.202007130005.

[7] R. F. Liu, L. J. Li, L. Zhang, Q. H. Geng, and Y. H. Li, "Simulation analysis of running stability of medium and low speed maglev train based on virtual prototype technology," Smart Rail Transit, vol. 59, no. 1, pp. 62-67, 2022. http://dx.chinadoi.cn/10.3969/j.issn.2097-0366.2022.01.012.

[8] Y. F. Yan, H. F. Qi, L. T. Luo, P. F. Liu, and K. L. Zhang, "Rigid-flexible coupled modeling of high-speed maglev vehicle and vibration transmitting research base on UM," *Railway Locomotive Car*, vol. 39, no. 5, pp. 59-64, 2019. http://dx.chinadoi.cn/10.3969/j.issn.1008-7842.2019.05.11.

[9] B. Wang, S. H. Luo, Q. Sun, K. R. Wang, and W. H. Ma, "Coherence analysis between vehicle vibration response of EMS maglev vehicles and track irregularities," *Electric Drive Locomotives*, vol. 2020, no. 2, pp. 113-117, 2020. http://dx.chinadoi.cn/10.13890/j.issn.1000-128x.2020.02.114.

[10] Y. W. Wang and Z. G. Lu, "Vertical dynamics simulation and stationarity study for maglev vehicle," Urban Mass Transit, vol. 2006, no. 8, pp. 39-42, 2006. http://dx.chinadoi.cn/10.3969/j.issn.1007-869X.2006.08.010.

[11] Y. Shi, W. Ma, M. Li, and Z. Xu, "Research on dynamics of a new high-speed maglev vehicle," *Vehicle Syst. Dyn.*, vol. 60, no. 3, pp. 721-742, 2022. https://doi.org/10.1080/00423114.2020.1838568.

[12] R. P. Talukdar and S. Talukdar, "Dynamic analysis of high-speed maglev vehicle–guideway system: an approach in block diagram environment," *Urban Rail Transit*, vol. 2, pp. 71-84, 2016. https://doi.org/10.1007/s40864-016-0039-8.

[13] C. F. Zhao and W. M. Zhai, "Maglev vehicle/guideway vertical random response and ride quality," *Vehicle Syst. Dyn.*, vol. 38, no. 3, pp. 185-210, 2002.

[14] Y. S. Hu, *XIANDAI GUIDAO CHELIANG DONGLIXUE*, Beijing: China Railway Publishing House, 2016.

[15] "Specification for dynamic performance assessment and testing verification of rolling stock," chinesestandard, 2019. https://www.chinesestandard.net/PDF.aspx/GBT5599-2019.

[16] Y. G. Sun, D. G. Gao, Z. Y. He, and H. Y. Qiang, "Influence of electromagnet-rail coupling on vertical dynamics of EMS maglev trains," *Mechatron. Intell Transp. Syst*., vol. 1, no. 1, pp. 2-11, 2022.