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INFLUENCE ANALYSIS OF TRACK IRREGULARITY ON RUNNING COMFORT OF MAGLEV TRAIN

Background: In this article, the TR08 car of the Shanghai Magnetic Train Demonstration Line was prototyped and a multi-body dynamics simulation model was established. And based on the low-interference track irregularity power spectrum in Germany, track irregularity data was obtained. Used dynamic simulation software, completed the dynamic simulation analysis of the vehicle-rail model controlled by the proportion-integral-derivative control system PID parameters. It can be concluded that the vibration of trains passing through irregular tracks at different speeds, and evaluated its comfort. The optimal solution for the control of the PID parameters of the train also has been derived.

Aim: Evaluation of operational comfort and suspension gap control effect of Shanghai Maglev Train Demonstration Line by simulation analysis.

Methods: Simulation analysis.

Results: The vibration acceleration and suspension gap of Shanghai Maglev Train Demonstration Line has been obtained.

Conclusion: By adjusting the parameters of PID control system, the vibration acceleration of train can be reduced and the ride comfort can be improved.

Keywords: Track irregularity, PID, Comfort, Maglev train.

INTRODUCTION

High-speed maglev train system is a complex multi-body dynamics system, the train's running speed can reach 430 km/h, ride comfort and stability performance are two important problems in the process of the maglev train running. Ju [1] et al. have conducted relevant research on the influence of track irregularity on the stability of train operation, and proposed a proportional-integral (PI) control method. By establishing a single magnet-levitation system-orbital beam interaction model, Li [2] et al. researched the effect of track irregularity on the variation of the suspension state of a single magnet. FAN Qin-Hai [3] analyzed the variation characteristics of the suspension gap of the suspended electromagnet by analyzing the vibration of the maglev vehicle under the track irregularity excitation. By multi-body dynamic simulation of the train, the stability of passenger comfort and suspension guide system under the condition of track irregularity was researched.

Based on the Shanghai maglev demonstration line's TR08 car as the prototype of the model, a multi-body dynamic simulation model of the entire

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maglev train system was built. In order to study the vibration of vehicle body and the stability of suspension guide system, the dynamic simulation analysis was carried out under the action of track irregularity. The main work includes the following:

Used the 3D modeling software to simplify the modeling of various parts of the TR08 model and conducted dynamic simulation of the model through an irregular road section. The track irregularity was based on the German's track irregularity power spectrum, by passing in different speeds to analyze the effect of track irregularity on the vehicle body's vibration response and the levitation gap stability at different vehicle speeds. Finally, summarized the dynamic performance of the model, included the ride comfort of the vehicle and the stability of the suspension system.

Vehicle Dynamics System Modeling

Used the three-dimensional modeling software and the dynamic simulation software to build a multi-body dynamics system model of a maglev train with a proportion- integral- derivative control system (PID).

The maglev train running mechanism was a complex multi-body movement mechanism. The levitation control system was also a unique system of maglev trains. A maglev train's car body consists of a carriage and four go-between mechanisms. The specific composition consists of a carriage, four suspension frames (eight suspension frames), 16 bolsters, 16 rocker levers, 4 traction devices, 14 Suspension electromagnet unit, 12 guide electromagnets, 2 brake electromagnets. There were also first and second suspension connection devices interconnected in Fig. 1.

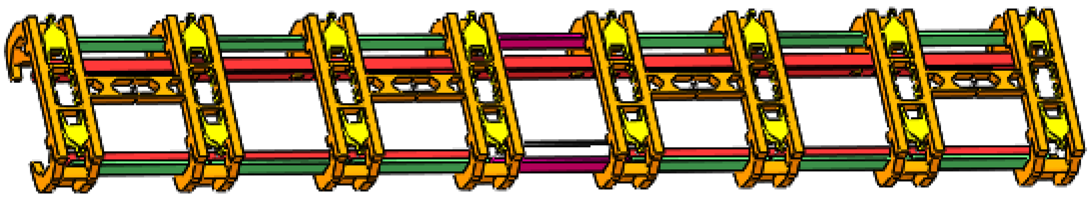

Fig. 1. Simplified model of the running mechanism

Taken each magnetic suspension, suspension electromagnets, guiding electromagnets, and compartment dynamics model as a substructure, and the overall model was a line moving platform. Then connected the suspension electromagnets and the guiding electromagnets between four suspension frames. Finally, the complete dynamic model of a maglev train was obtained by importing the substructure of the carriage. As shown in Fig. 2, there were 210 degrees of freedom for a maglev train model.

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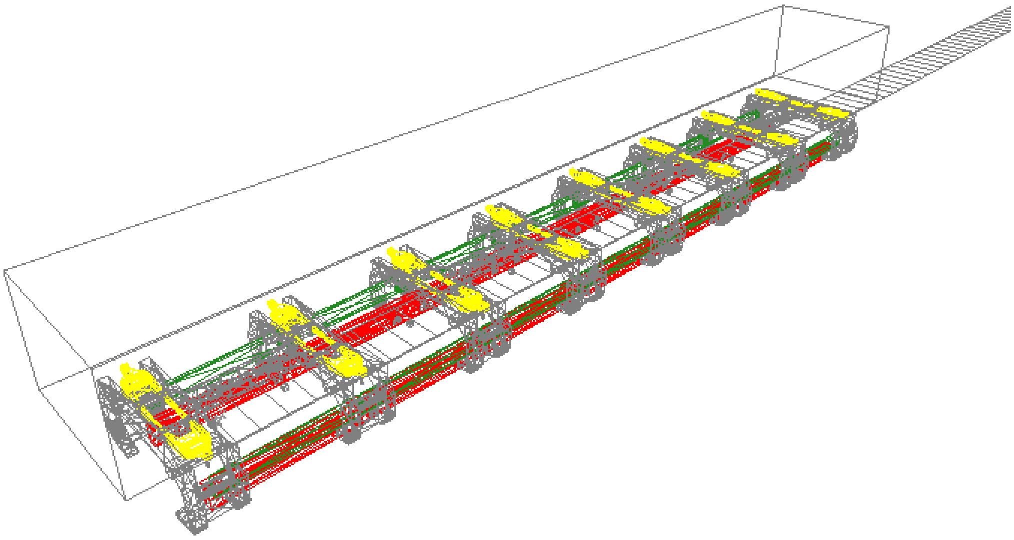

Fig. 2. Dynamic model of maglev train

COMFORT EVALUATION STANDARD

Through the study of Liu [4] et al. The International Organization for Standardization - Guidelines for the Impact of Vibration and Impact on People (ISO2631) [5] was selected as the comfort assessment standard. The comfort level was shown in table 1 [5].

Table 1. Classification of comfort levels

level	**Effective acceleration （m/s^2）**	**Evaluation**
1	<0.315	No discomfort
2	0.315~0.63	Slight discomfort
3	0.5~1.0	Moderately uncomfortable
4	0.8~1.6	Discomfort
5	1.25~2.5	Very uncomfortable
6	>2	Extremely uncomfortable

VIBRATION ANALYSIS UNDER TRACK IRREGULARITY

According to the merits of the country’s railway track, each country divides unevenness into different levels. The construction standards for the rail beams of maglev trains in Shanghai are very strict. The random irregularity is far less than the best rail track in the world. Its irregularity is mainly caused by the random variation of the coils laid on the rails instead of the deformation of the rail beams. The construction of the Shanghai maglev train track was based on the German rail construction standards. Therefore, when analyzing the multi-body dynamics, the German orbital irregular power spectrum [6, 7] was used as

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a benchmark. The German track grade is divided into two levels of high interference and low interference, to adapt to different speeds, in which the high interference level applies to speeds below 250 km/h, and the low interference level applies to speeds above 250 km/h. Due to the high standards of Shanghai's maglev train construction, one-tenth of the German low-interference spectrum can be used to express track irregularities. The vertical irregular power spectrum was shown in Equation 1 [7].

$$S_v = \frac{2.74162\times10^{-8}}{2.8855\times10^{-4}+0.68039\omega^2+\omega^4} \quad (1)$$

In which S_v, ω are the vertical power spectral density (1/(rad/m)) and the spatial frequency of the track irregularity (rad/m).

According to the above power spectrum function, the vertical spatial irregularity sample was shown in Fig. 3. Add the spatial irregularity sample to the orbit separately to simulate the dynamic performance of the vehicle through the uneven track.

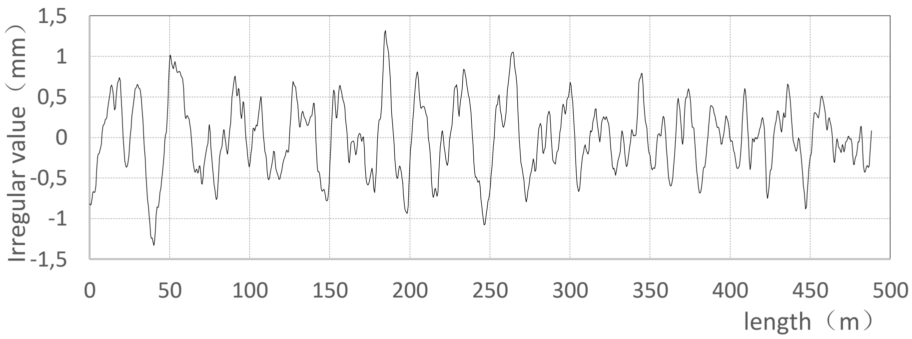

Fig. 3. Spatial Samples of Vertical Irregular

Input this vertical irregular track data to the established track model, and accelerate the speed to 100 km/h, 200 km/h, 300 km/h, 400 km/h, and 500 km/h with an acceleration of 1 m/s^2, measure the vertical acceleration of the three observation points on the vehicle body and the suspension gap variation of the suspended electromagnets, and analyzed the comfort of the vehicle and the stability of the suspension system.

When the maglev train was loaded with a vertical random irregular track at a speed of 100 km/h, the vertical vibration accelerations of the three vibration measurement points on the vehicle body and levitation gaps were shown in Fig. 4.

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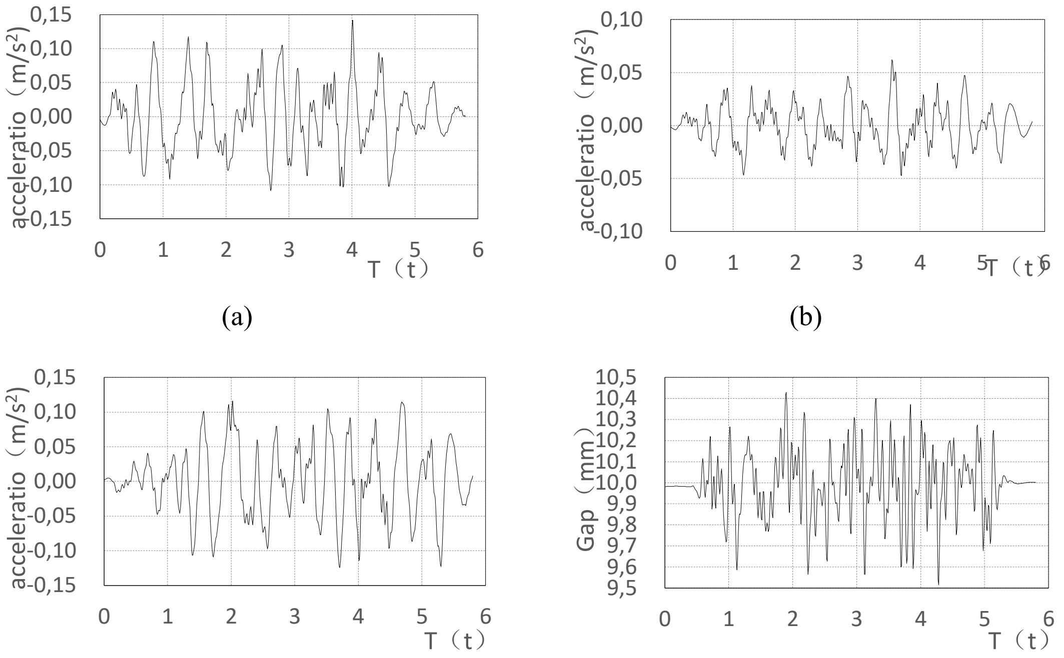

(a) (b)

(c) (d)

Fig. 4. Vertical Vibration Acceleration Curves of Front,
Middle and Tail of 100 km/h (a), (b), (c), and the suspension gap variation curve (d)

It could be calculated that the vertical effective accelerations of the front, middle and rear marking points of the carriage during the integration period were 0.048 m/s^2, 0.019 m/s^2, 0.052 m/s^2, the vertical effective vibration acceleration and the maximum vibration acceleration at the front, middle and rear of the carriage were all less than 0.315 m/s^2. Passengers would not feel uncomfortable and comfort level 1. In general, the vertical acceleration of the front part of the carriage and the rear part of the carriage were obviously greater than that of the central part of the carriage. The RMS value was approximately 2.6 times that of the middle part of the carriage. The vibration of the vehicle body was dominated by the nodding vibration.

Suspension gap was stable at 10 mm before and after entering the irregular track. The maximum suspension clearance was 10.43 mm at the irregular track, the minimum suspension gap was 9.52 mm. The maximum fluctuation of suspension gap was 0.48 mm, which was much less than 2 mm. The suspension system was basically in a stable state.

When the maglev train was loaded with a vertical random irregular track at a speed of 200 km/h, the vertical vibration accelerations of the three vibration measurement points on the vehicle body and levitation gaps were shown in Fig. 5.

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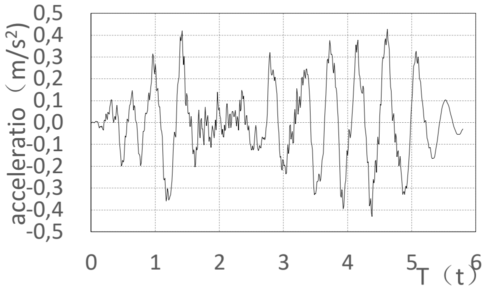

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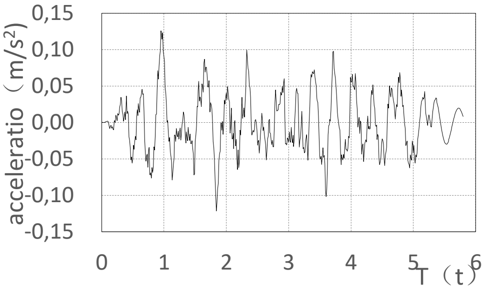

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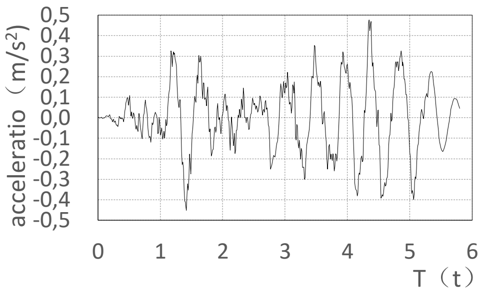

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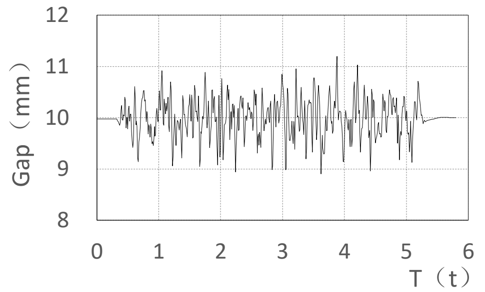

(d)

Fig. 5. Vertical Vibration Acceleration Curves of Front,
Middle and Tail of 200 km/h (a),(b),(c), and the suspension gap variation curve (d)

It could be calculated that the vertical effective accelerations of the front, middle and rear marking points of the carriage during the integration period were 0.17 m/s^2, 0.039 m/s^2, 0.16 m/s^2, the vertical effective vibration acceleration at the front, middle and rear of the carriage were all less than 0.315 m/s^2. Passengers would not feel uncomfortable and comfort level 1. In the front and the tail part of the carriage, the acceleration value exceeds 0.315 m/s^2 in some periods, and the maximum acceleration value was 0.48 m/s^2. Passengers will feel slightly uncomfortable as comfort level 2, duration was 1.1 s, about 18 % of the integration period. In general, the vertical acceleration of the front part of the carriage and the rear part of the carriage were obviously greater than that of the central part of the carriage. The RMS value was approximately 2.6 times that of the middle part of the carriage. The vibration of the vehicle body was dominated by the nodding vibration.

Suspension gap was stable at 10 mm before and after entering the irregular track. The maximum suspension clearance was 11.2 mm at the irregular track, the minimum suspension gap was 8.91 mm. The maximum fluctuation of suspension gap was 1.2 mm, which was much less than 2 mm. The suspension system was basically in a stable state.

When the maglev train was loaded with a vertical random irregular track at a speed of 300 km/h, the vertical vibration accelerations of the three vibration measurement points on the vehicle body and levitation gaps were shown in Fig. 6.

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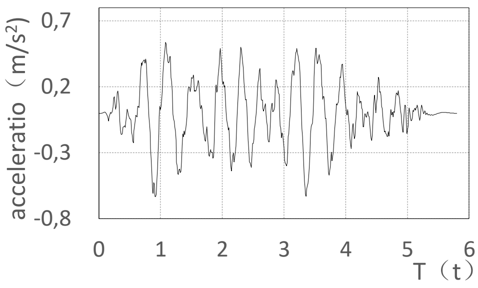
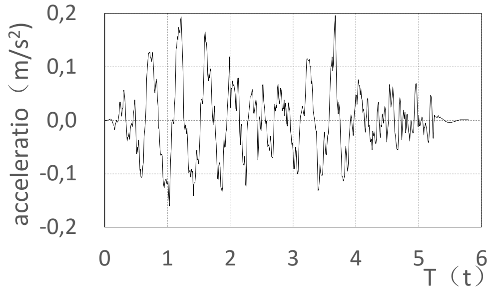


(a)



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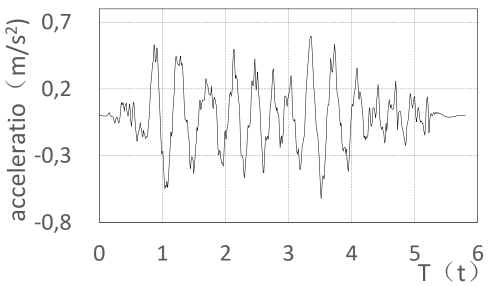

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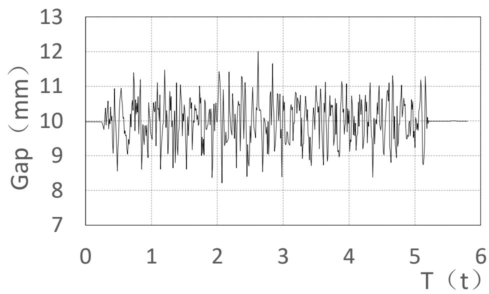

(d)

Fig. 6. Vertical Vibration Acceleration Curves of Front,
Middle and Tail of 300 km/h (a), (b), (c), and the suspension gap variation curve (d)

It could be calculated that the vertical effective accelerations of the front, middle and rear marking points of the carriage during the integration period were 0.23 m/s^2, 0.062 m/s^2, 0.22 m/s^2, the vertical effective vibration acceleration at the front, middle and rear of the carriage were all less than 0.315 m/s^2. Passengers would not feel uncomfortable and comfort level 1. In the front and the tail part of the carriage, the acceleration value exceeds 0.315 m/s^2 in some periods, and the maximum acceleration value was 0.63 m/s^2. Passengers would feel slightly uncomfortable as comfort level 3. However, it only appeared for a moment. Most of the time, the comfort level was grade 1 or 2, which accounted for 53 % and 47 % of the integration time period. In general, the vertical acceleration of the front part of the carriage and the rear part of the carriage were obviously greater than that of the central part of the carriage. The RMS value was approximately 3.6 times that of the middle part of the carriage. The vibration of the vehicle body was dominated by the nodding vibration.

Suspension gap was stable at 10mm before and after entering the irregular track. The maximum suspension clearance was 12.01 mm at the irregular track, the minimum suspension gap was 8.21 mm. The maximum fluctuation of suspension gap was 2.01 mm, which exceeds 2 mm, but the overshoot was very small and the suspension system was stable.

When the maglev train was loaded with a vertical random irregular track at a speed of 400 km/h, the vertical vibration accelerations of the three vibration

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measurement points on the vehicle body and levitation gaps were shown in Fig. 7.

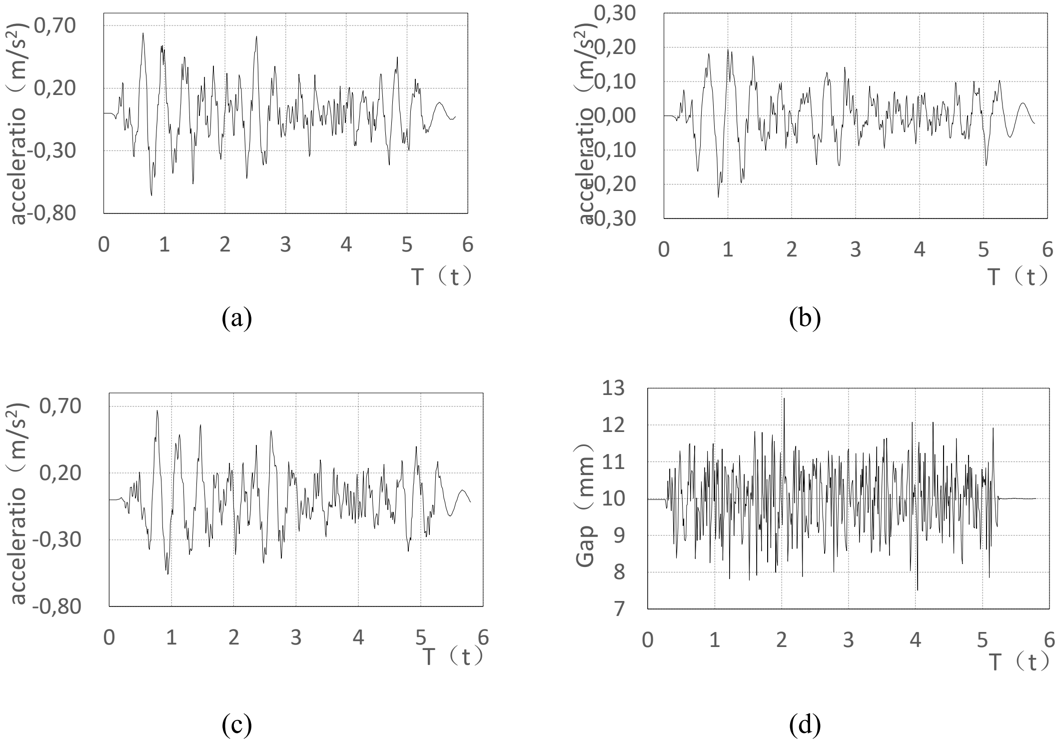

Fig. 7. Vertical Vibration Acceleration Curves of Front,
Middle and Tail of 400 km/h (a), (b), (c), and the suspension gap variation curve (d)

It could be calculated that the vertical effective accelerations of the front, middle and rear marking points of the carriage during the integration period were 0.21 m/s^2, 0.069 m/s^2, 0.20 m/s^2, the vertical effective vibration acceleration at the front, middle and rear of the carriage were all less than 0.315 m/s^2. Passengers would not feel uncomfortable and comfort level 1. In the front and the tail part of the carriage, the acceleration value exceeds 0.63 m/s^2 in some periods, and the maximum acceleration value was 0.67 m/s^2. Passengers would feel slightly uncomfortable as comfort level 3. However, it only appeared for a moment. Most of the time, the comfort level was grade 1 or 2, which accounted for 69 % and 31 % of the integration time period. In general, the vertical acceleration of the front part of the carriage and the rear part of the carriage were obviously greater than that of the central part of the carriage. The RMS value was approximately 2.9 times that of the middle part of the carriage. The vibration of the vehicle body was dominated by the nodding vibration.

Suspension gap was stable at 10mm before and after entering the irregular track. The maximum suspension clearance was 12.73 mm at the irregular track, the minimum suspension gap was 7.50 mm. The maximum fluctuation of suspension gap was 2.73 mm, which exceeds 2 mm, but the overshoot was very small and the suspension system was stable.

When the maglev train was loaded with a vertical random irregular track

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at a speed of 500 km/h, the vertical vibration accelerations of the three vibration measurement points on the vehicle body and levitation gaps were shown in Fig. 8.

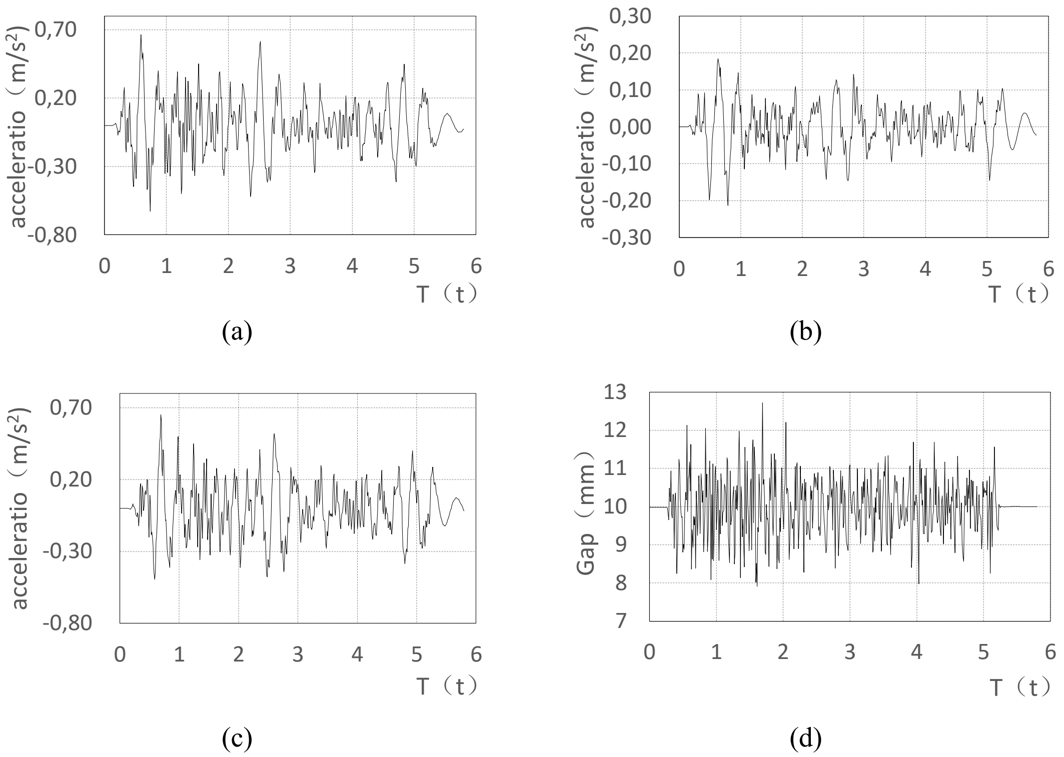

Fig. 8. Vertical Vibration Acceleration Curves of Front,
Middle and Tail of 500 km/h (a),(b),(c), and the suspension gap variation curve (d)

It could be calculated that the vertical effective accelerations of the front, middle and rear marking points of the carriage during the integration period were 0.2 m/s^2, 0.06 m/s^2, 0.16 m/s^2, the vertical effective vibration acceleration at the front, middle and rear of the carriage were all less than 0.315 m/s^2. Passengers would not feel uncomfortable and comfort level 1. In the front and the tail part of the carriage, the acceleration value exceeds 0.63 m/s^2 in some periods, and the maximum acceleration value was 0.66 m/s^2. Passengers would feel slightly uncomfortable as comfort level 3. However, it only appeared for a moment. Most of the time, the comfort level was grade 1 or 2, which accounted for 77 % and 23 % of the integration time period. In general, the vertical acceleration of the front part of the carriage and the rear part of the carriage was obviously greater than that of the central part of the carriage. The RMS value was approximately 3 times that of the middle part of the carriage. The vibration of the vehicle body was dominated by the nodding vibration.

Suspension gap was stable at 10mm before and after entering the irregular track. The maximum suspension clearance was 12.72 mm at the irregular track, the minimum suspension gap was 7.90 mm. The maximum fluctuation of suspension gap was 2.72 mm, which exceeds 2 mm, but the overshoot was very

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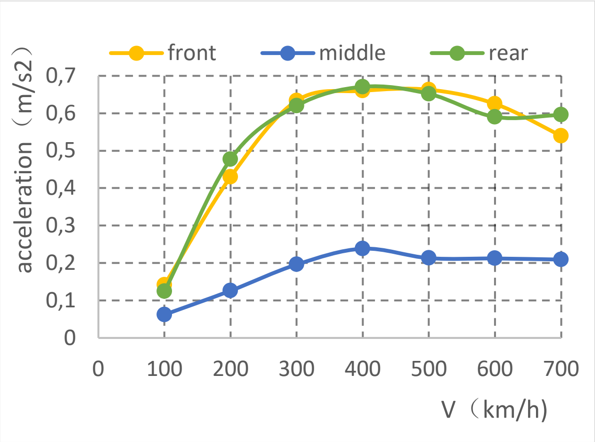
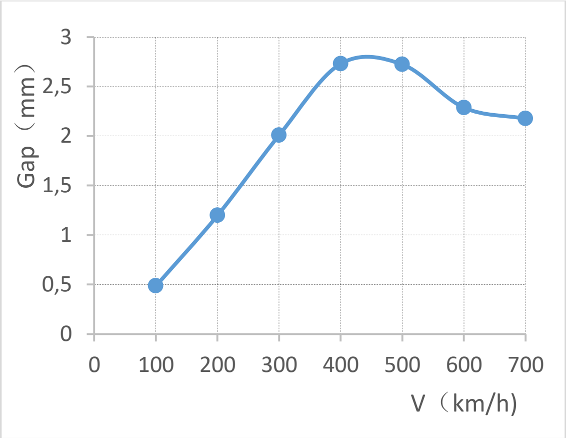
small and the suspension system was stable.

Continue to increase the speed, it can be found that the frame vibration acceleration and suspension gap fluctuations have a tendency to decline. Fig. 9 was the curve of the maximum vibration acceleration and suspension gap fluctuation of the vehicle body at a vehicle speed of 100 km/h ~ 700 km/h. It could be seen from the figure that the maximum value of vibration acceleration and the variation trend of the fluctuation of the suspension gap were inverted U-shape, the maximum value appears near the speed of 400 km/h, and the vertical maximum vibration acceleration appears at the rear of the compartment with the maximum value of 0.67 m/s^2, and the gap fluctuation was 2.73 mm.



(a)



(b)

Fig. 9. The curve of the maximum vibration acceleration(a), and suspension gap fluctuation of the vehicle body (b) at a vehicle speed of 100 km/h ~ 700 km/h

The normal operating speed of Shanghai high-speed maglev train was generally 430 km/h. This control effect was not the most effective, the usual approach was to increase the suspension stiffness, and reduce the suspension stiffness, increase the suspension stiffness could make the vibration peak moves backward, reduce the suspension stiffness could move the vibration peak forward. Due to the large levitation control stiffness of the maglev train, if the stiffness was increased, the peak value may continue to appear when the vehicle speed increases. Therefore, we adopted a method to reduce the levitation stiffness. After trials, it was reasonable to choose K_p to be 5.8 E6N/m, and T_i and T_d remain unchanged. The peak of the vibration and guidance gap move forward to about 300 km/h. The curve of the maximum vibration acceleration and suspension gap fluctuation of the adjusted model was shown in Fig. 10. When the train was running at normal speed, the vibration and suspension stability were better.

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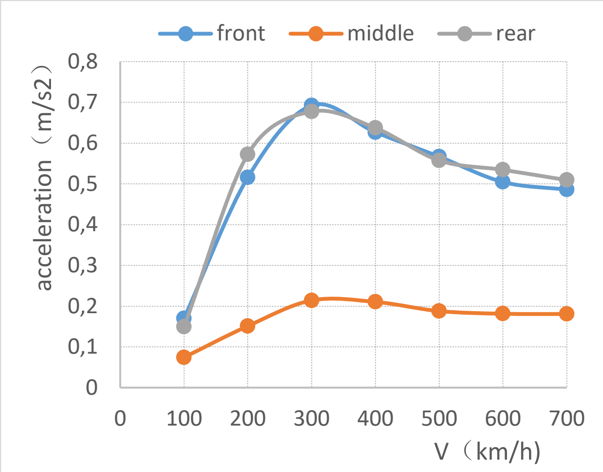
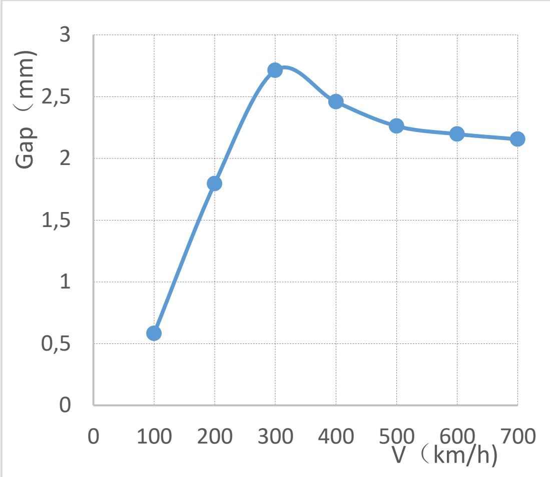


(a)



(b)

Fig. 10. the curve of the maximum vibration acceleration (a), and suspension gap fluctuation of the vehicle body (b) at a vehicle speed of 100 km/h ~ 700 km/h

CONCLUSION

Under the vertical irregular excitation of the track, the vertical acceleration of the vehicle body and the fluctuation of the suspension gap increased first and then decreased as the vehicle speed increased. Under the control of PID parameters, the vertical vibration acceleration of the car body and the peak value of the gap fluctuation of the suspension gap appeared at about 400 km/h. The passenger comfort level was class 1 in the compartment, 2 or 3 grades in some areas, and the fluctuation of the suspension gap was up to 2.73 mm. After adjusting the parameters of the PID, the peak value of the suspension gap appeared around 300 km/h, when the vehicle speed was 400 km/h, the maximum fluctuation of the suspension gap was 2.42 mm, which was reasonable.

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