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Research Article

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Research on sliding mode controller of high-speed maglev train under aerodynamic load

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Abstract

Maglev train is suspended through the surrounding track, which overcomes many disadvantages caused by the direct contact between the wheel and rail of traditional vehicles, such as excessive friction. It has the advantages of high speed, comfortable riding, less maintenance, strong climbing ability, and so on. However, when the train is running at high speed, it will be subjected to a strong unsteady aerodynamic load. The violent disturbance of aerodynamic load will inevitably lead to the corresponding feedback of electromagnetic force and the change of the suspension gap, which will affect the stability and safety of the train.

Keywords: High-speed maglev train; Aerodynamic load; Sliding mode controller; Primary suspension; Electromagnet fluctuation

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Introduction

The speed of the wheel-rail train is increasing gradually in order to meet the needs of people's life, but the increasing of speed will be restricted by the limit of wheel-rail adhesion. The appearance of the maglev train has changed this situation. The maglev train relies on the electromagnetic force between the levitation electromagnet and the track to realize suspension, and uses the guidance electromagnet to achieve the guidance function. Compared with the traditional vehicle, it has the advantages of low energy consumption, low environmental impact, low noise, less maintenance and strong climbing ability. In recent years, maglev train has made significant progress, and China's maglev system at 600 km/h has been launched on July 20, 2021. Since the aerodynamic load is directly proportional to the square of the speed, the aerodynamic load must increase sharply with the increase of the vehicle speed. Taking the of Shanghai maglev demonstration line as an example, the numerical calculation shows that if the train runs at 600 km/h, the average aerodynamic lift of the tail car can reach 10 tons, and the instantaneous lift can reach 14 tons when the train passing another train. The stable suspension of EMS high speed maglev vehicle is realized by controlled vertical electromagnetic force, such a large aerodynamic lift and impact will have momentous influence on the suspension stability and safety of the train. Kwon et al. [1] performed numerical simulation on the response of maglev vehicle passing through the suspension bridge and was subjected to gusts of wind. The research shows that the ride comfort of the maglev vehicle is reduced due to the low frequency vibration of the vehicle caused by the bridge and turbulence wind. Yau [2] considered the aerodynamic load caused by unstable air flow and calculated the response of the vehicle-guideway coupling system. The results show that the aerodynamic load may cause the significant acceleration amplification of the high-speed maglev vehicle. Wu and Shi [3] completed the numerical analysis of dynamic response of maglev vehicle body under wind field. Simulation of the lateral vibration response of maglev vehicle when it passing in open air has been completed by some Liu and Tian [4]. Takizawa [5] studied the comfort of the MLX01 Maglev train when it passing at 500 km/h.

For EMS maglev train, due to the inherent instability of electromagnetic levitation, it is necessary to exert control on the levitation system to maintain stable operation, therefore, the response of EMS maglev train under external disturbance is closely related to the control algorithm. At present, the control algorithm of high-speed maglev train is still based on PID control, which realizes feedback control by calculating the acceleration of electromagnet and the difference between actual gap and rated gap. However, PID control does not involve the parameters of vehicle system and external disturbance. When the train is subjected to the aerodynamic load and impact, the control algorithm does not change with it, which is easy to cause the fluctuation and instability of suspension gap. Common state feedback control is difficult to meet the control requirements, so algorithms such as neural network control, genetic algorithm control and sliding mode control have been used to magnetic levitation system. Among them, sliding mode control is gradually carried into the control of magnetic levitation system because of its strong robustness and anti-disturbance. In recent years, many scholars have applied sliding mode control technology to the levitation control of maglev train.

Molero et al. [6] used the sliding mode control to the magnetic levitation ball to control the position of the nonlinear system composed of the iron ball and the electromagnetic coil. Wang [7] analyzed a single-axis magnetic levitation system and then designed an adaptive sliding mode control which could deal with unknown parameters to complete the guidance and positioning of the system. Bandal et al. [8] designed a sliding mode controller for position control of electromagnet, which based on the concept of proportional integral switching surface, and compared it with the feedback linearization controller. Yang et al. [9] developed a new dynamic sliding surface by combining the disturbance estimation value and its high-order derivative information, and proposed a continuous dynamic sliding mode control (CDSMC) method that can be used in suspension control system. Benomair et al. [10] proposed a fuzzy sliding mode controller (FSMC) which can estimate the unmeasured state using a nonlinear observer. In order to study the influence of air resistance on the dynamic response of maglev train, Gao et al. [11] proposed an operation control method based on sliding mode periodic adaptive learning control (SM-PALC) to reduce the position error and improve the robustness of the control system. Dourla et al. [12] designed a dynamic sliding mode controller by controlling the current through the electromagnetic coil. Chen et al. [13] introduced sliding mode control into the research of flexible track of maglev train, and designed the sliding mode adaptive state feedback controller of maglev system, then compared with PID controller, it is found that the controller can guarantee faster dynamic response and stronger robustness when considering flexible orbit disturbance. A hybrid flux density observer based on current and voltage feedback is proposed by Xu et al. [14], and an adaptive sliding mode controller is designed to reduce the parameter uncertainty and disturbance upper bound of the sliding mode controller.

Sliding mode control has the characteristic of variable structure, it can force the system to move according to the state trajectory of the predetermined "sliding mode" in the dynamic process according to the current state of the system, to overcome the uncertainty of the system. Because the sliding mode can be designed and is independent of parameters and disturbances, it has the advantages of fast response, insensitivity to parameter changes and disturbances, no need for on-line identification of the system and simple physical implementation. In order to overcome the influence of the aerodynamic load and suppress the vibration of the electromagnet during the running of the train, the sliding mode control technology is adopted in this paper to design the suspension controller of the maglev train. However, due to the fact that the aerodynamic loads on maglev trains cannot be measured and obtained in real time during the operation of trains, how to introduce the influence of aerodynamic disturbances conveniently and effectively, so that the sliding mode controller can change its structure in time when it is subjected to aerodynamic load and impact, no scholar has given a solution at present.

Given that the vibration caused by the aerodynamic load and impact acting on the maglev train body will be transmitted to the electromagnet through the secondary suspension, the maglev frame and the primary suspension, so the fluctuation of primary suspension force can be regarded as the disturbance of aerodynamic load to the electromagnetic suspension system. Therefore, this paper considers the influence of primary suspension force disturbance on a single point suspension system, and derives a sliding mode controller considering the influence of primary suspension deformation disturbance. Based on TR08 maglev train, the dynamic simulation model of high-speed maglev train with three vehicles is presented. Then, the sliding mode controller is applied to the maglev train, and the dynamic response of the high-speed maglev train passing in open air is calculated, the control results are compared with those of PID controller and sliding mode controller without considering the primary suspension distortion disturbance. The analysis shows that compared with PID controller, sliding mode controller can perform better in restraining the vibration response of the maglev train under aerodynamic load. Moreover, considering the primary suspension deformation disturbance in the sliding mode controller, the load on the train can be reflected into the control process, so that the suspension gap of the train can be controlled and adjusted more effectively.

Single point suspension model

A single point two-stage suspension model was established in this paper, as shown in **Fig. 1**. A sliding mode controller can be presented on the basis of this model.

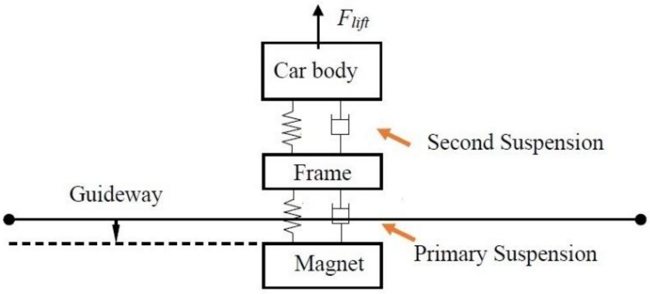

Fig. 1 Schematic diagram of single point two-stage suspension system

The vertical motion equation of the electromagnet can be written as:

$$m\ddot{z} = mg - F(i, z) + f_{st}(t) + f_{unst}(t) \tag{1}$$

The levitation force between the electromagnet and the guide rail is calculated by the classical electromagnetic force formula as follows:

$$F(i, z) = \frac{\mu_0 A N^2 I^2}{4z^2} \tag{2}$$

In Eq. , μ_0 is the air permeability, z is the suspension gap, A is the effective area of the electromagnet, N is the turns of the coil, $f_{st}(t)$ and $f_{unst}(t)$ represent the balance value and the fluctuation of primary suspension force, respectively.

The maglev train directly adjusts the current in the electromagnet through the suspension control unit. The dynamic equation can be written as follows:

$$\ddot{z} = -\frac{\mu_0 A N^2}{4m}\left[\frac{I(t)}{z(t)}\right]^2 + g + \frac{f_{st}(t) + f_{unst}(t)}{m} \tag{3}$$

Let$x_1 = z(t)$, $x_2 = \dot{z}(t)$, the state equation of the electromagnet levitation system can be written as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = -\frac{\mu_0 A N^2}{4m}\left[\frac{I(t)}{x_1(t)}\right]^2 + g + \frac{f_{st}(t) + f_{unst}(t)}{m} \end{cases} \tag{4}$$

Set $\left[\frac{I(t)}{x_1(t)}\right]^2$ as u to design the suspension controller, and rewrite the dynamic equation as:

$$\ddot{z} = -\frac{\mu_0 AN^2}{4m}u + g + \frac{f_{st}(t)+f_{unst}(t)}{m} \tag{5}$$

The state equation is rewritten as:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = -\frac{\mu_0 AN^2}{4m}u + g + \frac{f_{st}(t)+f_{unst}(t)}{m} \end{cases} \tag{6}$$

or

$$\dot{\boldsymbol{X}} = \boldsymbol{AX} + \boldsymbol{B}\left(-\frac{\mu_0 AN^2}{4}u + mg + f_{st}(t) + f_{unst}(t)\right) \tag{7}$$

Where, $\boldsymbol{A} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \boldsymbol{X} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T, \boldsymbol{B} = \begin{bmatrix} 0 & \frac{1}{m} \end{bmatrix}^T$.

The dynamic model of maglev train with three vehicles

The dynamic model of single vehicle TR08 maglev train is shown in **Fig. 2**. Each vehicle is mainly composed of the following parts: car body (1 piece), frame (4 pieces), pillow beam (8 pairs), pendel (8 pairs), traction pull rod (4 pieces), traction/suspension magnet (8 pairs for intermediate vehicle and 7.5 pairs for lead vehicle), brake magnet (1 pair), guide magnet (6 pairs), air spring (8 pairs), car body transverse elastic holder or rubber spring, traction/suspension electromagnet and suspension frame unit support (16 pairs for intermediate vehicle and 15 pairs for lead vehicle) , brake electromagnet support, etc.

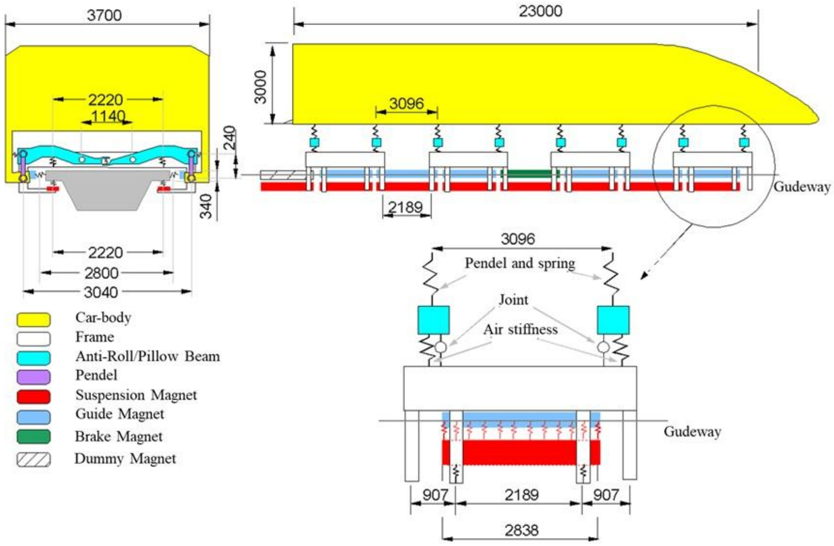

Fig. 2 Vehicle dynamics model

In the modeling, because the suspension frame is connected by two C-shaped frames, and the longitudinal beam connected in the middle has large flexible deformation, each suspension frame is simplified into two semi-maglev frames, which are connected through component. Other parts are considered as rigid bodies and their flexible deformation is ignored. The suspension structure of the vehicle embodies the independence of stiffness in: the vertical, transverse and longitudinal traction of the secondary system are provided by air spring, pendel and lateral additional spring/holder and traction device, respectively. The primary suspension is independently provided by supporting rubber parts or arthrosis structures of the traction electromagnet and the guide (including brakes, replacements) electromagnet. The track and vehicle are coupled by electromagnetic force, and the suspension electromagnetic force is actively controlled by the control system, so as to realize the suspension of the vehicle.

In this paper, the dynamic simulation model of train was established by using multi-body dynamics software. Based on the dynamic model shown in **Fig. 2**, a simulation model of TR08 single vehicle was established, then the maglev train with three vehicles was formed, which is shown in **Fig. 3**, and the position of electromagnet on each train is marked in the figure.

Fig. 3 Dynamic model of TR08 maglev train

In this paper, the train was controlled dispersedly, so that the design of the whole vehicle suspension control system could be completed by designing the single electromagnet suspension control system, which could make the control system more simplified. Each suspension electromagnet of TR08 train has 12 coils, six of which share one control unit, and each control unit is independent of each other. This paper used SIMULINK to simulate the control module, based on the sliding mode control technology proposed in this paper, the single channel suspension control scheme is present as follows:

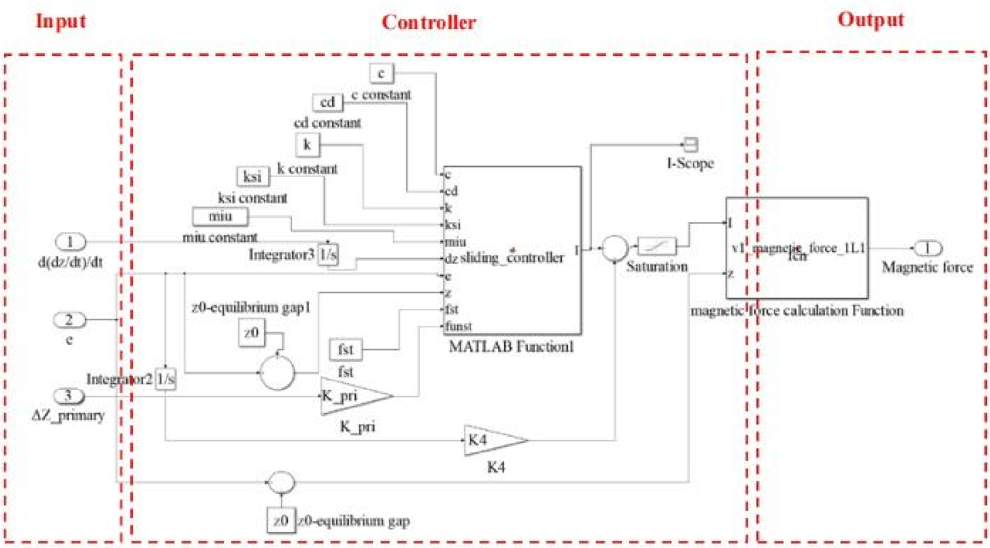

Fig. 4 Single channel SMC suspension control system model

On the basis of the dynamic simulation model and the suspension control model of the train with three vehicles, the data transmission of the multi-body dynamic model and the control model is realized through the SIMAT interface in MATLAB, so as to realize the coupling simulation between multi-body dynamics and suspension control of TR08 train. Each single channel control unit consists of input, controller and output. Each control unit receives the fluctuations of electromagnet suspension gap, acceleration and primary suspension force obtained by vehicle dynamics simulation, calculates these data to obtain the desired current value, then calculates the output electromagnetic suspension force, and finally returns it to the vehicle dynamics simulation model.

At the same time, in order to demonstrate the control effect of the proposed sliding mode controller, this paper also used the PID control algorithm as the comparison. The single channel PID controller is shown in **Fig. 5**.

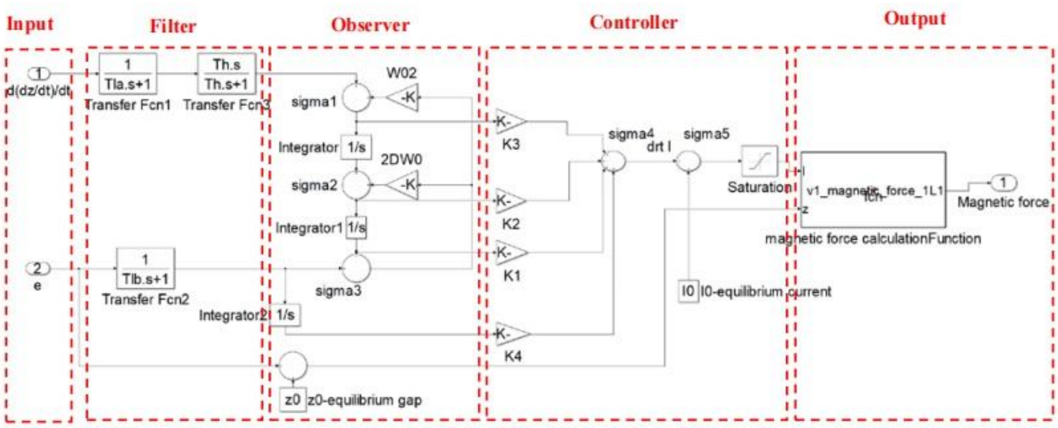

Fig. 5 Single channel PID suspension control system model

Each single channel PID control unit is composed of filter, observer and controller. The estimated value in the state observer is a weighted combination of air gap, velocity and acceleration. Each control unit receives the electromagnet suspension gap and acceleration that input from the vehicle dynamics model, then these signals are filtered and observed through the SIMULINK, and the electromagnetic levitation force is calculated by the controller and fed back to the dynamic simulation module.

Analysis of train response under aerodynamic load

(1) Aerodynamic load data

Based on the CFD method, the aerodynamic load of the train passing in open air at 300 km/h, 400 km/h and 500 km/h was simulated. Under different operating speeds, the variation of aerodynamic load curve acting on the train is basically the same, but with the increase of vehicle speed, the amplitude of load will also increase. The aerodynamic lateral force, lift force and pitching moment on the train when it runs at 500 km/h are shown in **Fig. 6**. The aerodynamic moment is the result of taking the center of mass of car body as the moment point. The blue, green and orange solid lines in the figures represent the aerodynamic load on the head, middle and tail vehicle of the train during operation, respectively, while the range covered by the black dotted line in the figure represents the passing stage of the train in the open air. Obviously, when the train is running, the tail train receives the largest aerodynamic load, followed by the head car, the middle car is smaller. It is noted that the aerodynamic load fluctuates obviously in the train passing stage.

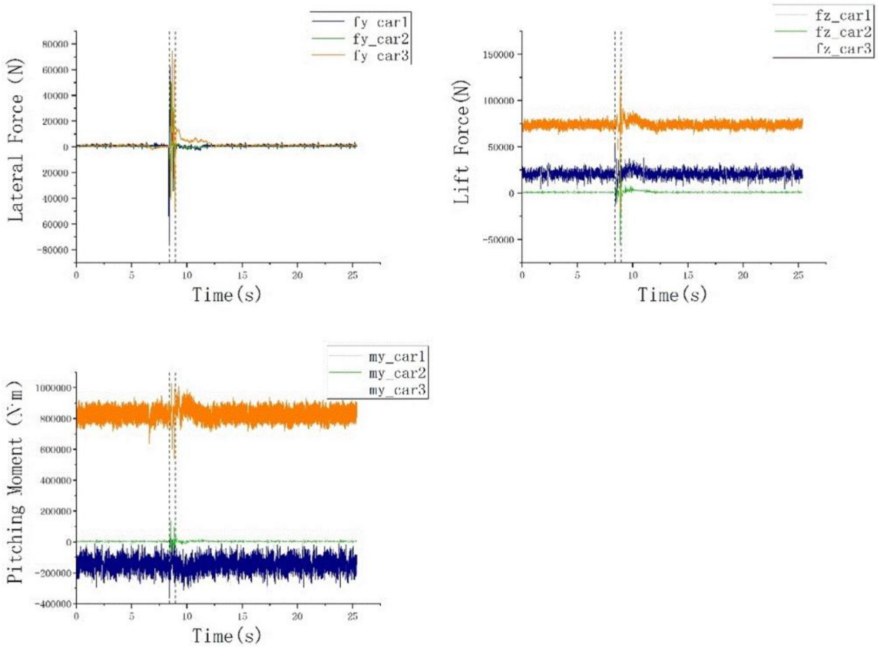

Fig. 6 Aerodynamic load at 500 km/h

This paper applied the above aerodynamic force and moment to the vehicle centroid in the dynamic model, carried out the motion simulation of maglev train under aerodynamic loads, then compared the dynamic response of the train under using PID control, traditional sliding mode control (SMC) and sliding mode control considering primary suspension disturbance (SMC_P), including the vehicle ride quality, the displacement of the train and the gap fluctuation of electromagnets. In PID control, feedback control parameters are set to: K_1=7000, K_2=200, K_3=0.5, K_4=1000. The parameters of sliding mode controller are set to: c=100, ξ=20, k=80, K_{pri}=-2×10^7/6.0.

(2) Car body response analysis

The results about Sperling ride index of trains running at different speeds in open air under aerodynamic loads are shown in **Table 1**.

Table 1 Comparison of vertical Sperling ride index

Speed (km/h)	Car body	PID (mm)	SMC (mm)	SMC_P (mm)
300	Head car	1.330317	1.334163	1.332673
	Middle car	1.138362	1.144525	1.151148
	Tail car	1.670477	1.693833	1.710850
400	Head car	1.479943	1.506137	1.513859
	Middle car	1.250410	1.493161	1.503598
	Tail car	1.922125	1.904598	1.891828
500	Head car	2.289424	2.317263	2.334752
	Middle car	1.608220	1.618358	1.626261
	Tail car	2.021350	2.001179	1.982947

It is apparent that Sperling ride index of the train gradually increases with the increase of speed. In the case of PID control, traditional sliding mode (SMC) control and sliding mode with primary suspension force disturbance (SMC_P), the results about Sperling ride index have little difference and are all less than 2.5, which means the train has excellent stability.

Table 2 shows the heave motion amplitudes of the car body under using three controllers when it is passing in open air at different speeds. It is obvious that the vertical vibration amplitude of the head train is the smallest and the tail train is the largest under the different speeds, and the vibration amplitude of the train increases gradually with the raise of the speed. Under the three controllers, the vertical vibration amplitudes of the car body are close and the response results are excellent.

Table 2 Vertical vibration amplitudes of the car body

Speed (km/h)	Car body	PID (m)	SMC (m)	SMC_P (m)
300	Head car	0.0144051	0.0142736	0.0144051
	Middle car	0.0115441	0.0114622	0.0115441
	Tail car	0.0426626	0.0424268	0.0426626
400	Head car	0.0229016	0.023062	0.023111
	Middle car	0.0191232	0.0190864	0.0190421
	Tail car	0.0693106	0.0693116	0.0692293
500	Head car	0.0583298	0.0585040	0.0585755
	Middle car	0.0310934	0.0312598	0.0313184
	Tail car	0.0951066	0.0945006	0.0939576

(3) Levitation gap response of electromagnet

Fig. 3 shows the distribution of electromagnets in the train. **Fig. 7** - **Fig. 9** show the fluctuation curves of the electromagnet levitation gap on the right at positions H1, M1, M9 and T7 when the train is running at different speeds. The black dotted line corresponds to the time when the two train meet and separate.

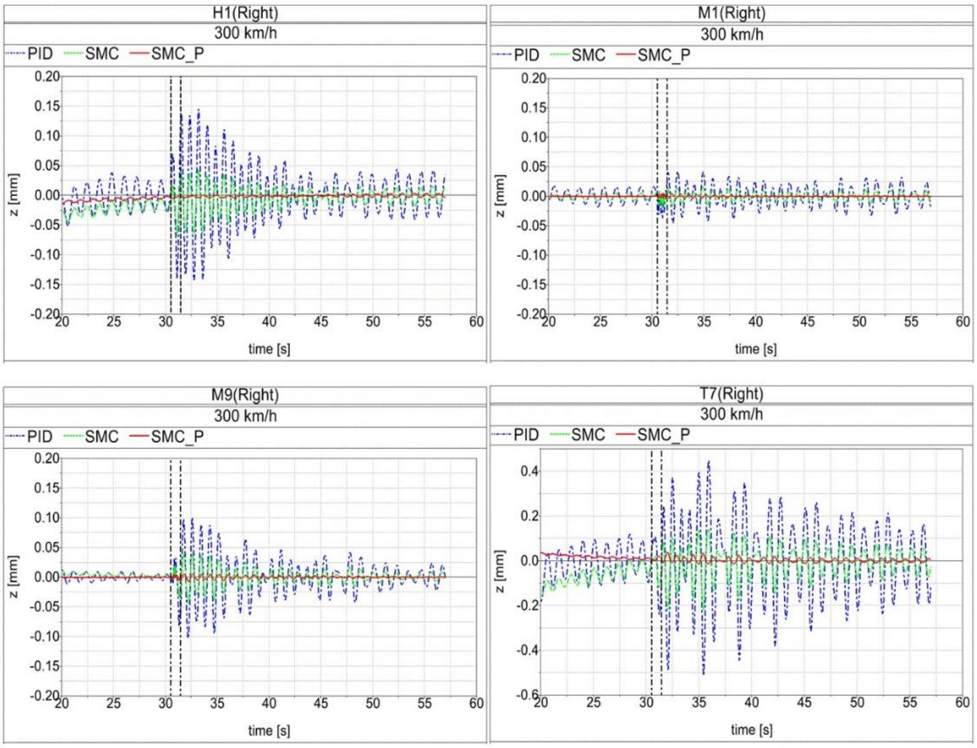

Fig. 7 Electromagnet gap fluctuation at 300 km/h (Negative ordinate represents upward movement of electromagnet)

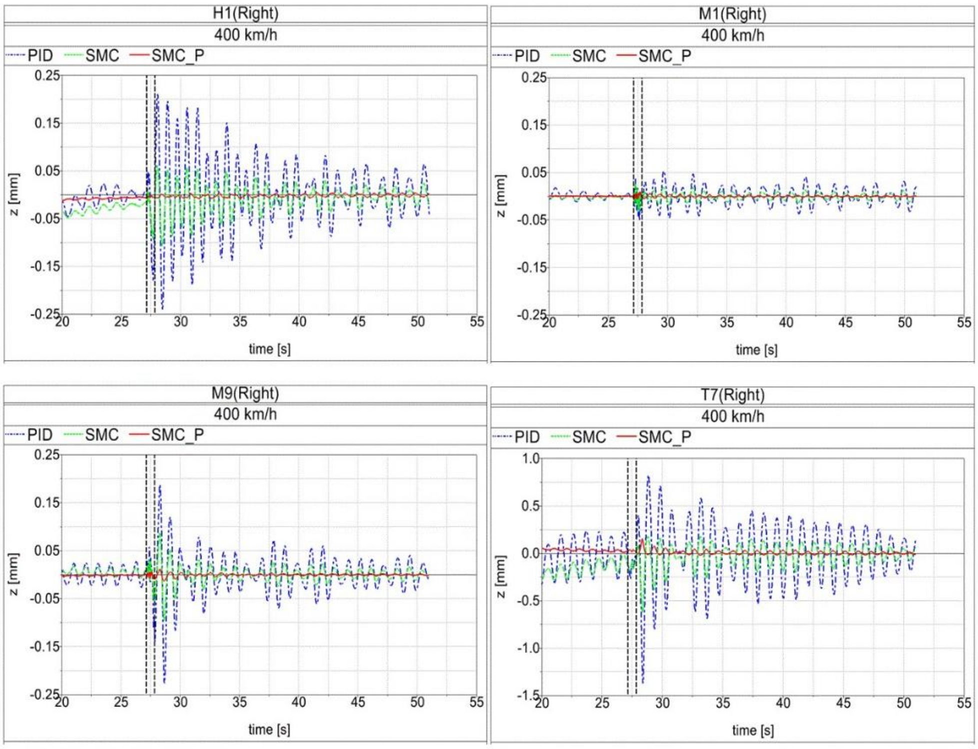

Fig. 8 Electromagnet gap fluctuation at 400 km/h

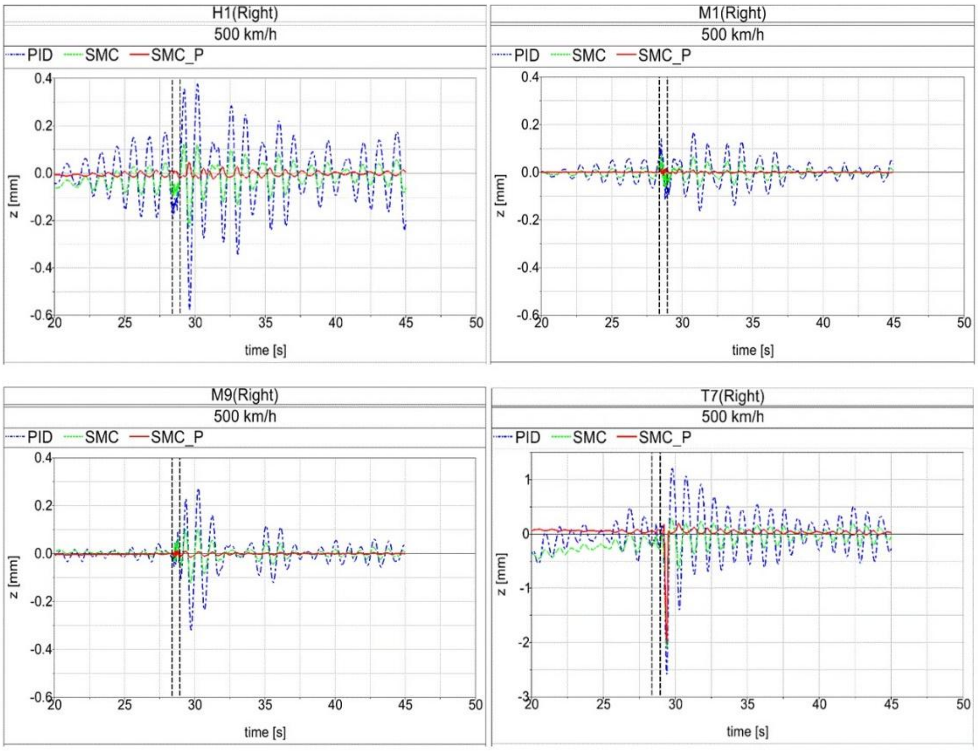

Fig. 9 Electromagnet gap fluctuation at 500 km/h

Obviously, using the sliding mode controller considering the primary suspension deformation disturbance designed in this paper, the gap fluctuation values of electromagnet at the head, middle and tail vehicle are smaller than those when using the traditional sliding mode control. Compared with using traditional PID controller, it has more excellent performance and good suspension stability.

Declaration

Availability of data and materials

Not applicable.

Competing interests

The Authors declare that there is no conflict of interest.

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Authors' contributions

Mengjuan Liu: Data curation, Writing- Original draft preparation, Software, Formal analysis.

Han Wu: Conceptualization, Methodology, Funding acquisition, Article check, Supervision.

Xiaohui Zeng：Funding acquisition, Supervision.

Bo Yin: Improve data.

Zhanzhou Hao: Improve data.

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Not applicable.

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