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A NOVEL DESIGN OF ELECTROMAGNETIC LEVITATION SYSTEM FOR HIGH-SPEED MAGLEV TRAIN

Aim: To reduce the levitation energy consumption and alleviate the adverse effects caused by the over-heating of the electromagnet.

Methods: The design and manufacturing of hybrid electromagnet are introduced firstly. Secondly, the modification of driving chopper module together with a levitation control strategy and the design of an adsorption-prevention module are presented in details. Thirdly, a complete two-carriage maglev train is upgraded with the proposed hybrid electromagnet, choppers, and adsorption modules. Finally, an experiment is performed on a 1.5 km high-speed maglev test line to prove the efficiency of the proposed system.

Results: In this paper, a novel electromagnetic levitation system architecture and safety protection strategy for the high-speed maglev train are proposed.

Conclusion: A novel design of electromagnetic levitation system for high-speed maglev train is designed and implemented.

Keywords: High-speed maglev train, Levitation system, Hybrid permanent magnet and electromagnet, Chopper, Adsorption prevention.

1. INTRODUCTION

The high-speed maglev train is an intercity high-speed rail transportation tool with broad application prospects [1]. The first commercial high-speed maglev line in the world is located in Shanghai, China. The train was officially opened in 2002. It adopts the German TR08 technology and has been operating safely and stable for over 15 years. The successful operation of the Shanghai Maglev line shows the advantages of the maglev train, such as high speed, safety, stability, and low maintenance costs [2].

However, TR08 uses electromagnetic levitation technology without permanent magnet and keeps the train suspending on the track through pure electromagnetic attraction, which causes the following problems:

1. The levitation needs large current which causes serious over-heating of electromagnet [3].

2. The current is close to saturation and the payload capacity is limited.

3. The power supply equipment is very large and occupies too much vehicle space and quality.

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4. The over-heating affects the life expectancy of the electromagnet and the working environment of sensors [4, 5]. In order to solve these problems [6, 7], this paper presents a novel hybrid permanent magnet and electromagnet levitation system for high-speed maglev train. The permanent magnet can generate parts or all of the static levitation force, and the electromagnetic coil mainly plays the role of dynamic adjustment. Hybrid permanent magnet and electromagnet levitation system can significantly reduce the levitation energy consumption and the heating of electromagnet.

This paper mainly focuses on the hybrid permanent magnet and electromagnet levitation system for the high-speed maglev train. It includes the structural design of hybrid levitation electromagnet, the modeling of hybrid levitation system, the design of the levitation controller, the design of power drive module, strategies of adsorption prevention, and the evaluation experiments of a two-carriage maglev train.

2. DESIGN SCHEME OF HYBRID LEVITATION ELECTROMAGNET

Levitation force of high-speed maglev based on electromagnetic levitation is generated by the current in levitation electromagnet. The levitating cost is about 1000 W/t [8]. Fig. 1 is the schematic diagram of the levitation electromagnet for the high-speed maglev train.

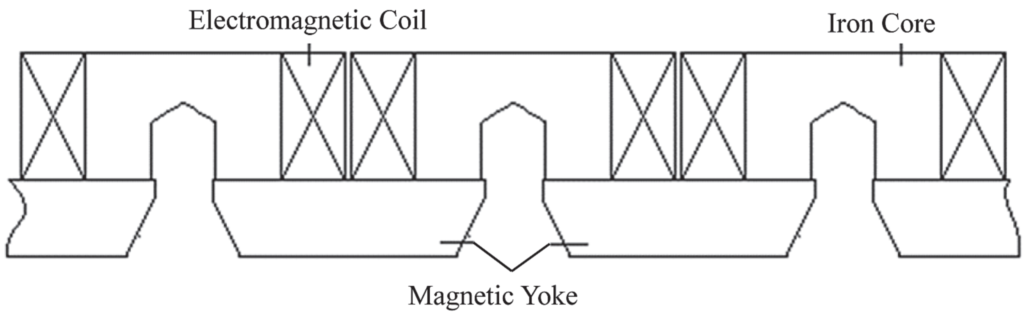

Fig. 1. The schematic diagram of levitation electromagnet

The hybrid high-speed maglev train levitation system proposed in this paper adds permanent magnet material (NdFeB) into the system except for the existing electromagnet. In order to make full use of the permanent magnet, the popular structure of the hybrid electromagnet is discussed first.

According to the different installation position of the permanent magnet, there are mainly three different schemes.

The first scheme: As shown in Fig. 2, the permanent magnet is installed in the middle of the core. In this way, the permanent magnet will not change the

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external dimensions of levitation magnets, and electromagnetic coils and yokes do not need to be changed. However, since the permanent magnet is added into the core, the winding of the electromagnetic coil become more difficult, so the core needs to be redesigned. Moreover, since the polar area of the permanent magnet is equal to the polar area of the iron core, the polar area of the permanent magnet cannot be selected flexibly.

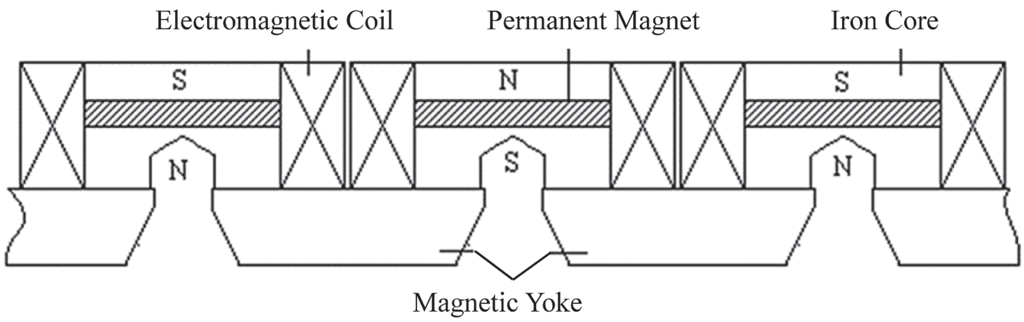

Fig. 2. The first PEM structural diagram.
The permanent magnet is installed in the middle of the iron core

The second scheme: As shown in Fig. 3, the permanent magnet is installed between the iron core and the yoke. In this way, iron cores, electromagnetic coils, and yokes do not need to be changed. However, the polar area of the permanent magnet is small, and it cannot be adjusted flexibly.

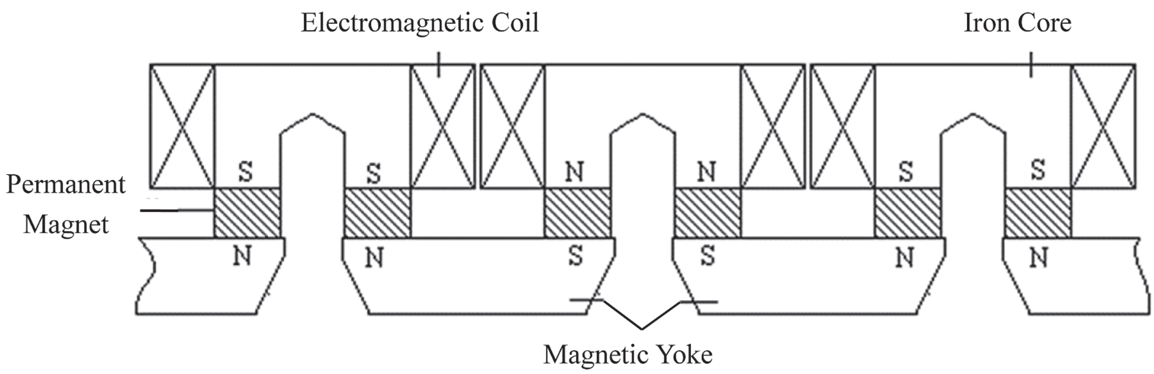

Fig.3. The second PEM structural diagram.
The permanent magnet is installed between the core and the yoke

The third scheme: As shown in Fig. 3, the permanent magnet is installed in the middle of the yoke. In this way, Iron cores and electromagnetic coils do not need to be changed, and the polar area of the permanent magnet can be selected flexibly. However, the yoke needs to be redesigned.

Adding the permanent magnet into the middle of the base yoke can not only increase the touching area of the permanent magnet, but also protect the permanent

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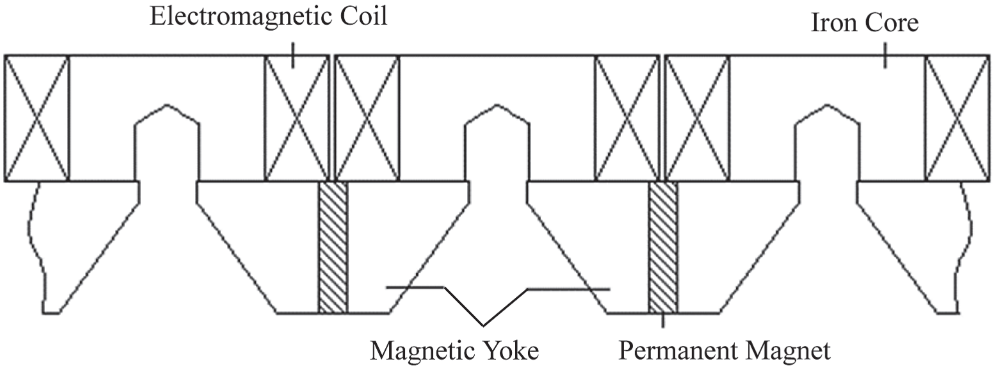

Fig. 4. The third PEM structural diagram.
The permanent magnet is installed in the middle of the yoke

magnet through the yoke. Compared with the way of installing permanent magnet above the core of the electromagnet, this installation way can avoid permanent magnet hitting the track and protect the electromagnet structure. Therefore, the structure of the hybrid permanent magnet and electromagnet adopts this installation mode. The calculation of the electromagnetic attraction in Fig. 4 can use the equivalent structure shown in Fig. 5. Variables are defined as follows: μ_0 denotes the permeability of vacuum, μ_r denotes the relative permeability of the permanent magnet, N denotes numbers of coil turns, i denotes the current in the coil, u denotes the control voltage at both ends of the coil, H_c denotes the coercivity of the permanent magnet, B_r denotes the remanence of permanent magnetic materials, H_m denotes the magnetic field strength at permanent magnet, H_z denotes the magnetic field strength at the gap, B_m denotes the magnetic induction strength at permanent magnet, B_z denotes the magnetic induction strength at the gap, Φ denotes the magnetic flux in magnetic circuit, $M_{\max}$ denotes the full load quality, $M_{\min}$ denotes the no-load quality, z denotes the levitation gap, z_m denotes the permanent magnet thickness, z_0 denotes the steady state levitation gap, S denotes the cross section area at the top of the core, S_m denotes the polar area of permanent magnet, F denotes the force between the permanent magnet and the orbit, $I_{\max}$

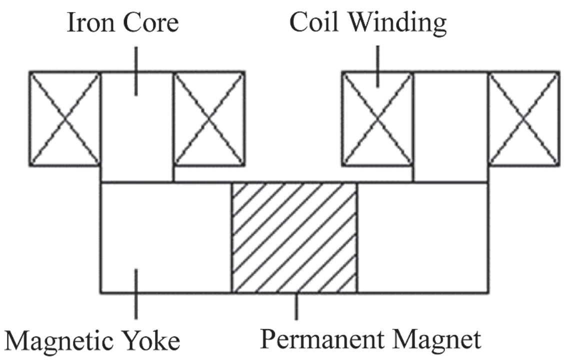

Fig. 5. The equivalent structure of the hybrid electromagnet

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denotes the allowed positive maximum current, $I_{\min}$ denotes the reverse maximum current, $I_{0\max}$ denotes the maximum current of steady state levitation, z_{00} denotes the gap of adsorption, z_{inital} denotes the floating gap.

The total reluctance of the closed loop R_m is calculated from the formula of reluctance:

$$R_m = z_m / (\mu_0 \mu_r \cdot S_m) + 2z / (\mu_0 \cdot S) \quad (1)$$

The total magnetic motive force U_m of the closed loop is shown below:

$$U_m = Ni + H_c z_m \quad (2)$$

According to the conversion relation between magnetic motive force and reluctance, magnetic flux Φ satisfies the following equation:

$$\Phi = U_m / R_m = \frac{Ni + H_c z_m}{z_m / (\mu_0 \mu_r \cdot S_m) + 2z / (\mu_0 \cdot S)} \quad (3)$$

According to the calculation formula of the magnetic induction force and magnetic force at the gap, the magnetic force F can be obtained by:

$$F = \frac{B_z{}^2}{2\mu_0} \cdot (2S) = \frac{\Phi^2}{\mu_0 S} = \frac{\mu_0 S (Ni + H_c z_m)^2}{(2z + z_m S / (\mu_r \cdot S_m))^2} \quad (4)$$

For the convenience of calculation, the formula of magnetic force can be simplified as:

$$F = \frac{K(\alpha i + 1)^2}{(z + \beta)^2} \quad (5)$$

3. LEVITATION MODELING AND THE DESIGN OF THE CONTROL ALGORITHM

In terms of control law design, the German scholar E. Gottzein first established the decentralized control mode of maglev train relying on mechanical decoupling and single point independent control. This mode is still in use today, and it determines the structure design and electrical control mode of high-speed and low-speed maglev train. In the mode of decentralized control, the study of suspension control is generally based on single point model. The suspension control law is designed by using multiple information, such as suspension gap, gap differential, electromagnet acceleration, acceleration integral, electromagnet current and voltage, and magnetic flux density of electromagnet. The mathematical model of the single point suspension system of the hybrid permanent magnet and electromagnet is shown follows:

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$$\begin{cases} m\ddot{z} = mg + N_s - F = mg + N_s - \dfrac{K(\alpha i+1)^2}{(z+\beta)^2}_e \\ u = Ri + \dfrac{d}{dt}(Li) = Ri + \dfrac{\mu_0 N^2 S}{2z + z_m S/\mu_r S_m}\dfrac{di}{dt} - \dfrac{2\mu_0 NS(Ni + H_c z_m)}{(2z + z_m S/\mu_r S_m)^2}\dfrac{dz}{dt} \end{cases} \quad (6)$$

Assuming the state variable as $x = [x_1\ x_2\ x_3] = [z\ z'\ i]$, the state equation can be obtained by:

$$\begin{cases} x_1' = x_2 \\ x_2' = -\dfrac{K(\alpha x_3+1)^2}{m(x_1+\beta)^2} + \dfrac{N_s}{m} + g \\ x_3' = \dfrac{-Rx_3(2x_1 + z_m S/\mu_r S_m)}{\mu_0 N^2 S} + \dfrac{2\mu_0 NS(Nx_3 + H_c z_m)}{(2x_1 + z_m S/\mu_r S_m)^2}x_2 + \dfrac{(2x_1 + z_m S/\mu_r S_m)}{\mu_0 N^2 S}u \end{cases} \quad (7)$$

The system model is a typical nonlinear system, which is usually complicated. A simple method is to linearize the system at the equilibrium point and get a linearized model. The stability of the linearized model near the equilibrium point can be considered as consistent with the stability of the original model.

Let $x' = 0$, the equilibrium point can be obtained by:

$$x_0 = [x_{10}\ x_{20}\ x_{30}] = \left[z_0 \quad 0 \quad \frac{1}{\alpha}[\sqrt{\frac{(mg+N_s)}{K}}(z_0+\beta) - 1] \right] \quad (8)$$

Linearize the system model at the equilibrium point, and the state space expression after linearization is obtained by:

$$\begin{cases} \Delta x' = A_S \Delta x + B_S \Delta u = \begin{bmatrix} 0 & 1 & 0 \\ a_{21} & 0 & a_{23} \\ a_{31} & 0 & a_{33} \end{bmatrix} \Delta x + \begin{bmatrix} 0 \\ 0 \\ b_{31} \end{bmatrix} \Delta u \\ \Delta y = C_S \Delta x = [1 \quad 0 \quad 0] \Delta x \end{cases} \quad (9)$$

where: $a_{21} = \dfrac{2K(\alpha i_0 + 1)^2}{m(z_0+\beta)^3}$,

$$a_{23} = -\frac{2K\alpha(\alpha i_0 + 1)}{m(z_0+\beta)^2},$$

$$a_{33} = \frac{-K(2z_0 + z_m S/\mu_r S_m)}{\mu_0 N^2 S},$$

$$b_{31} = \frac{2z_0 + z_m S/\mu_r S_m}{\mu_0 N^2 S}.$$

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A cascade control idea is adopted in levitation control of maglev train in general, by introducing the current negative feedback, the current response speed is increased.By selecting appropriate feedback parameters, the current feedback link can be simplified as a proportional link with a gain of 1, which simplifies the complexity of controller design. Set state variable as $[x_1, x_2] = [z, z']$, the single point suspension system can be reduced to two order system. Then the state equation can be presented as follows:

$$\begin{cases} x_1' = x_2 \\ x_2' = -\dfrac{K(\alpha u + 1)^2}{m(x_1 + \beta)^2} \end{cases} \tag{10}$$

Let $x_1' = x_2' = 0$, the equilibrium point can be obtained by $x_{10} = z_0$, $x_{20} = 0$, $u_0 = i_0 = \frac{1}{\alpha}[\sqrt{\frac{(mg+N)}{K}}(z_0 + \beta) - 1]$. Linearize the state equation at the equilibrium point:

$$\begin{bmatrix} \Delta x_1' \\ \Delta x_2' \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{2K(\alpha i_0 + 1)^2}{m(z_0 + \beta)^3} & 0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{2K(\alpha i_0 + 1)}{m(z_0 + \beta)^2} \end{bmatrix} \Delta u \tag{11}$$

According to optimal control theory for linear two order problems, the performance index is as follows:

$$J = \int_0^\infty \left[x^T(t) Q x(t) + u^T(t) R u(t) \right] dt \tag{12}$$

where Q, R are the weighting coefficients for state variables and control variables.

The optimal control variable to minimize the performance index is shown below:

$$u^*(t) = -R^{-1} B^T P x(t) = -Kx(t) \tag{13}$$

where P is the unique solution of the Riccati algebraic equation:

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{14}$$

4. DESIGN OF POWER DRIVE MODULE

The difference between the hybrid permanent magnet and electromagnet levitation system and the normal electromagnet system is that even if there is no current in the coil, the hybrid electromagnet still has attraction force. Because of the magnetic force of the hybrid electromagnet can make the electromagnet adsorbed on the track when failures occur. As shown in Fig. 6, the bi-directional chopper must be used in the hybrid levitation system, and the chopper drive circuit must

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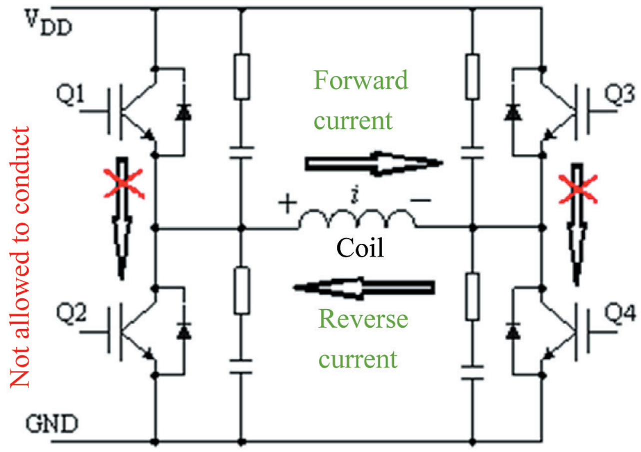

Fig. 6. A bi-directional chopper for hybrid levitation system

be able to output voltage in two directions. The two power switches in the upper part and the lower part of the bi-directional chopper are connected in a branch. In order to avoid direct connection, the opening period of the two devices must have no overlap. In this way, it can avoid the burning of the power components. So the safe and reliable driving of the power switch tube must be solved.

In order to avoid the direct connection between the upper and lower bridge arms, a chopper drive circuit with perfect function and high reliability should be selected. The external RC network generates suitable dead time to avoid simultaneous conduction of upper and lower bridge and main power supply short circuit. Drive circuit has perfect short circuit protection, over current protection and power monitoring function. If abnormal occurs, the block signal will be enabled and the chopper will turn off four power switches at the same time.

5. DESIGN OF ADSORPTION PREVENTION

Because the adsorption fault can cause great damage to levitation system and affects the safety of the maglev train, it is necessary to design the adsorption protection module for the permanent magnet. In order to improve the reliability of protection strategy, this paper designs a novel adsorption prevention module from the perspective of control algorithm and mechanical design.

5.1. Adsorption preventing by control algorithm design

By improving the design of the levitation controller and chopper, the system can have the function of adsorption prevention. The structure of the designed adsorption prevention system is shown in Fig.7.

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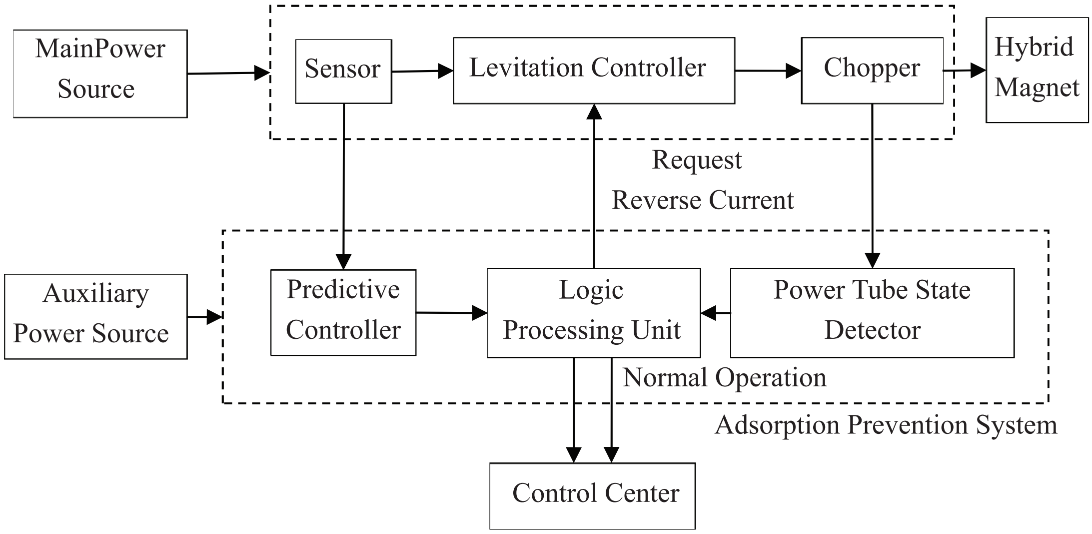

Fig. 7. The Schematic diagram of the proposed adsorption prevention system

The adsorption prevention system consists of a predictive controller, a power transistor state detector, and a logic processing unit. Under normal circumstances, the adsorption prevention system predicts the gap and monitors the chopper state, and the levitation controller adjusts the current according to the algorithm. When there is a risk of adsorption, the levitation controller outputs the reverse current to reduce the attraction between the magnet and rail track.

The realization of the adsorption prevention system through the digital circuit is shown in Fig. 8. The DSP predicts the effect of levitation control. When the actual value is quite different from the predicted value, the DSP judges that the levitation control has failed and sends a protection order to the CPLD. The CPLD is used to generate PWM waves and outputs fault-oriented safety PWM.

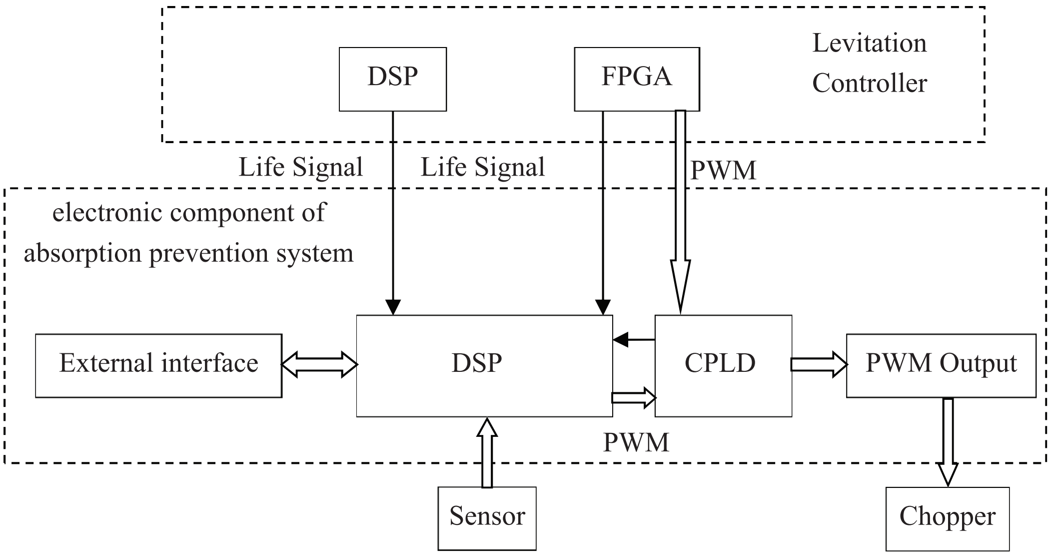

Fig.8. The hardware structure of the adsorption prevention system

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5.2 Adsorption preventing by mechanical design

Except for the control method, design a novel mechanical structure is another method to keep a minimum gap between the electromagnet and the track when absorption failure occurs. In this way, the direct collision between the magnetic pole and the track can be avoided, and the repair difficulty is greatly reduced after adsorption failure occurs. The specific mechanical design method is to add pads on both ends of the electromagnet. The pad is 3.5mm higher than the magnetic pole, which ensures there is a 3.5mm minimum gap between the electromagnet and the track.

6. EXPERIMENTAL RESULTS

In order to ensure the safety of the system, a lot of experiments need to be performed before it can be put into usage. Experimental tests mainly focus on ensuring system security. The tests include the static levitating and landing test carried out in the garage, the normal suspension of the system, artificially disturbance applied for the levitation electromagnet to evaluate the proposed adsorption prevention methods, and implementing the tests on the track outside the garage. Those key experiments are performed and evaluated in this section.

6.1. Levitation experiment

The static levitating and landing test is carried out in the garage. Fig. 9 shows the assembled high-speed maglev train based on hybrid permanent magnet and

Fig. 9. The high-speed maglev train based on hybrid permanent magnet and electromagnet in Shanghai

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electromagnet in Shanghai. Fig. 10 shows the experimental result of the maglev suspension. After the levitation command is issued, the levitation electromagnet gradually rises to the target position, meanwhile the levitation gap decreases gradually and keeps at the target value. Fig. 11 shows the test result of the landing process. After the landing command is issued, the electromagnet rapidly falls to the initial position, and the levitation gap gradually increases from the target value to the initial value.

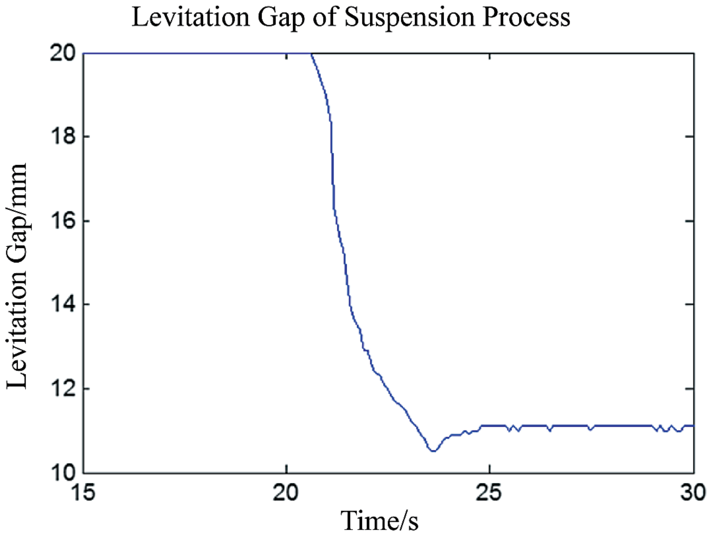

Fig. 10. Levitation gap during the maglev suspension

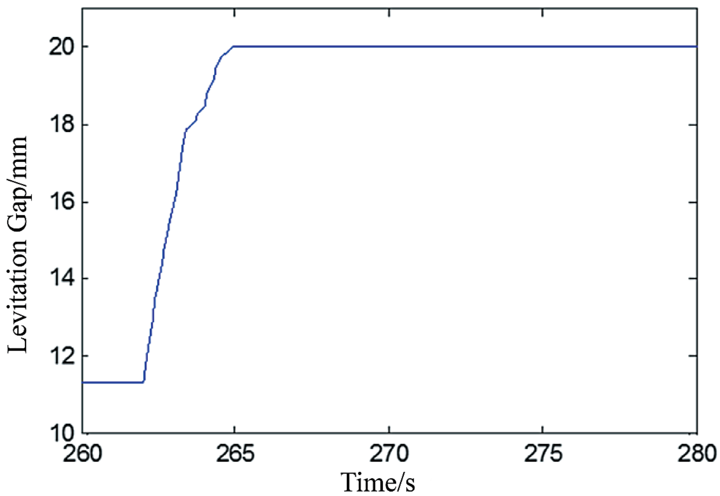

Fig. 11. Levitation gap during landing process

6.2. Operation experiment

The traction test of 2 maglev trains based on the hybrid permanent magnet and electromagnet on 1,5 km track is also carried out, the test result is shown in

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Fig. 12. The levitation gap remains stable during this process, and the amplitude of the electromagnet fluctuates within 3 mm.

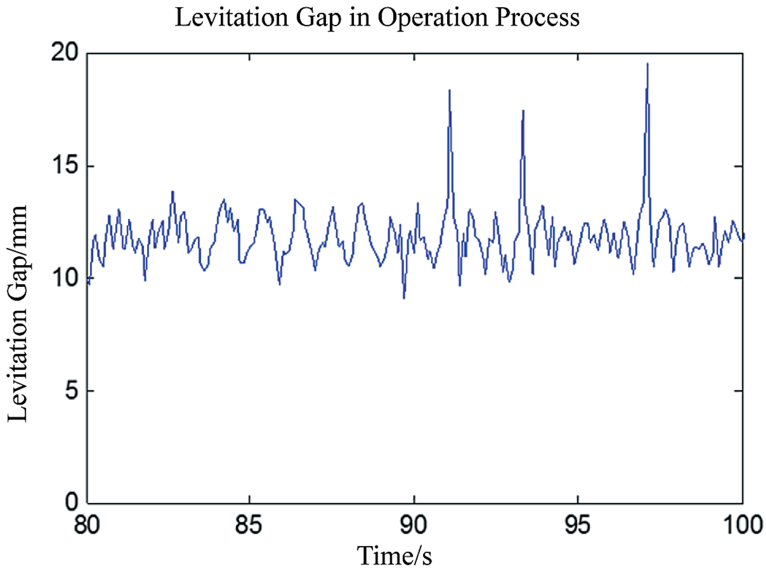

Fig.12. Levitation gap during running test

7. CONCLUSIONS

The hybrid permanent magnet and electromagnet levitation system has two characteristics, one is energy conservation, and another one is payload capacity. In order to make full use of these two advantages, the hardware design and control algorithm need to be modified in order to solve new problems of the hybrid permanent magnet and electromagnetic levitation system. In this paper, a two-marshaling maglev train based on the hybrid permanent magnet and electromagnet levitation is reformed, the stable levitation of the train is achieved, the closed loop traction test is carried out, and the feasibility of high-speed maglev train based on the hybrid permanent magnet and electromagnet levitation technology is verified.

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