Chapter 2
Technology Development and Application Research of Maglev Control

Suspension control, traction control, and operation control technologies are three key technologies of the electromagnetic suspension Maglev train [1]. Traction control and operational control in the wheel-rail transportation system have been fully studied and applied. Compared with the suspension control technology, the traction control and operation control technologies have relatively matured [2–4]. Since the Maglev suspension control technology is unique, it is still very necessary to study it in engineering applications [5, 6].

2.1 Introduction

In essence, the electromagnetic suspension system is unstable. Hence, the active suspension control must be applied to ensure the stability of trains and realize the train operation without mechanical contact. In addition, the suspension system performance directly influences the safety and comfort of Maglev train. Meanwhile, due to the complexity of the controlled object and the uncertainty of operation environment, the suspension control technology is always the difficulty and the core issue of the EMS Maglev train [7–9].

The suspension control system mainly comprises suspension sensors, suspension controllers, suspension choppers, supply power, and other auxiliary equipment. The controllers are the core of the suspension control system [10–12]. The suspension control principle is shown in Fig. 2.1.

The suspension sensors can measure the gap between the electromagnet and the track, and the current and motion state of electromagnets, which are fed back to the suspension controller. The suspension controllers can compare the measured value with the set value of levitation gap. If the measured value is greater than the set value, the control quantities are calculated and output based on the control law. The control voltage across the electromagnet is increased through the suspension

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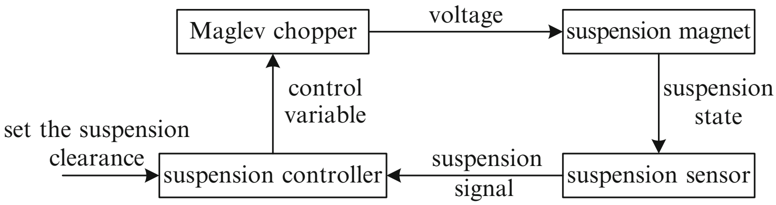

Fig. 2.1 Control structure of suspension system

chopper, and the suspension current is added to increase the electromagnetic force, which can make the electromagnet upward move and reduce the suspension gap. Otherwise the control voltage is decreased to reduce the electromagnetic force, so that the downward movement of the electromagnet is carried out and the suspension gap is increased. In addition, in order to improve the performance of suspension system, the suspension controller can provide the damping for the suspension system by the speed feedback. The current response speed of the electromagnet can be improved through the current response [13–15].

The suspension system structure of Maglev train is complex and the model is strongly nonlinear. In addition, due to the external disturbances and parameter perturbation, the system model has greater uncertainty. The suspension control system must ensure the stability of the Maglev train under various conditions, which is a basic requirement of Maglev technologies.

2.2 Suspension Control Plan of Maglev Train

The low-speed EMS Maglev train uses the hierarchical structure based on the "module" concept, and the module is an independent unit that integrates the suspension, guidance, and traction functions [16–18]. The unit interior contains four suspension electromagnets, which are divided into two groups and formed two suspension endpoints through the interaction with the track. Two modules form a bogie by the connection of anti-roll beams. Several bogies form the suspension system of Maglev train through the interaction between electromagnetic force and track. For the suspension control technology research, we can choose a suspended endpoint, a module, or Maglev train as the controlled object. The following several control schemes can be presented, namely, single electromagnet suspension control scheme, suspension control module scheme, centralized control scheme, and overlapping suspension control scheme [19–21].

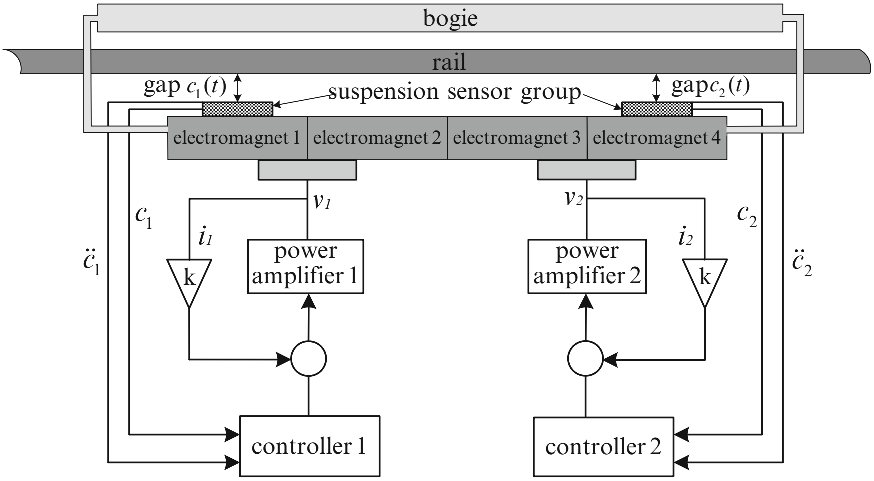

Fig. 2.2 The structure of single point suspension control system

2.2.1 Single Electromagnet Suspension Control Scheme

Two group electromagnets inside the module are equivalent to two completely independent single electromagnets, so the module can be simply divided into two separately controlled objects as shown in Fig. 2.2. Since the module is a rigid body, the states of two suspension end point will affect each other, particularly when the state of a suspension endpoint is adjusted due to over rail joints or disturbed.

For the suspension control scheme of single electromagnet, this kind of interference is considered as the outside interference of system and can be passively suppressed by increasing the robustness of the control algorithms. At present, most of the suspension control algorithms are based on the control scheme design and analysis of single electromagnet suspension.

Using two power amplifiers, two controllers can control four electromagnets, and each controller is corresponding to two series connection electromagnet. Controller 1 only receives the signals from the left sensor groups, and controller 2 only receives the signals from the right sensor groups, namely, the system is divided into two completely separate controlled subsystems. The method only requires fewer components and lower cost, but it is affected by the coupled [22–25].

2.2.2 Module Suspension Control Scheme

For the state of the module suspension system coupled problem, through the decoupled control algorithm design, the module is considered as the controlled

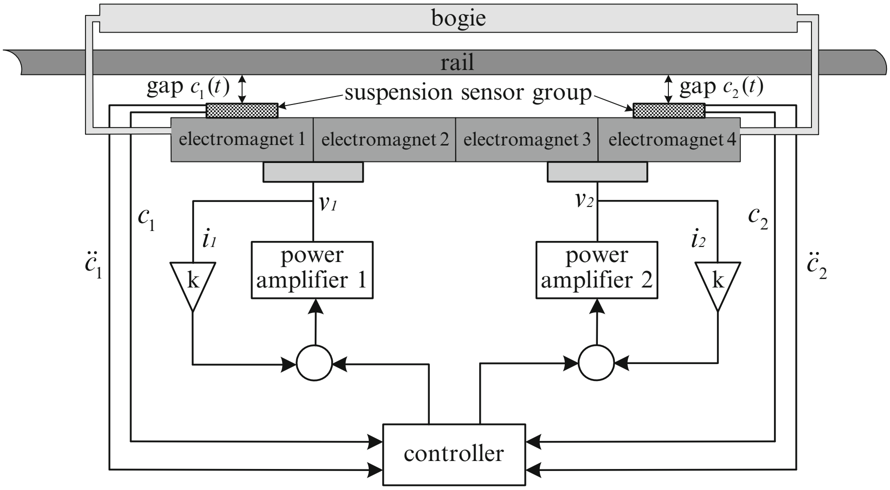

Fig. 2.3 The structure of module suspension control system

object, which can actively suppress the mutual coupling between the internal modules of two suspended endpoints [26–28]. The way can improve the suspension system performance without increasing system cost, which is shown in Fig. 2.3.

Only one controller in the entire module is used to control two pairs of electromagnets. The corresponding electromagnets for each pair electromagnets are connected in series. The plan requires a minimum of component parts and is the most economical plan. The controller can receive the signals from the sensors of two end points in the module. It is unnecessary to divide the system in the plan, but the whole module as a complete system is decoupled. The plan that combines the information at both ends of the sensor can effectively eliminate the influence of mechanical coupling ends of the module. The controller uses a redundant structure to improve system reliability. However, any electromagnet or amplifier controller failure will lead to the suspension failure.

2.2.3 Concentrated Suspension Control Scheme

A bogie or Maglev train is considered as a controlled object; a controller is adopted to complete its suspension control. The centralized control structure requires a mathematical model of a bogie or Maglev train system, and the comprehensive multiple suspension points to obtain the status information of controlled objects with the sensor signals, which results in the complex structure of suspension control system and the difficult control algorithm design.

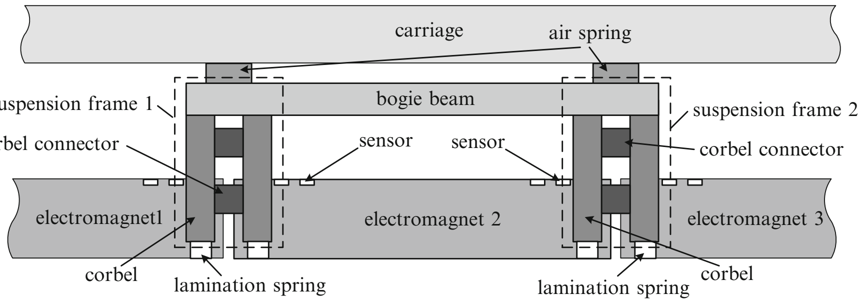

Fig. 2.4 Overlapping suspension control scheme

2.2.4 Overlapping Suspension Control Scheme

In order to ensure the redundancy of suspension system, the overlapping suspension control scheme can be adopted for high-speed Maglev train. Each suspension frame has two suspension arms, and the two suspension arms via an upper connection component and a lower connection component are connected by a bolt, which can form the overall stiffness and elasticity. The suspension electromagnets are mounted on the frame between two adjacent suspension frames. So, two suspension arms of a suspension frame are corresponding to different suspension electromagnets, and they can form the overlapping suspension structure. In two suspension units of the overlapping structure, two sensors are respectively equipped with, which can make the suspension system have redundancy capabilities when pass the rail joints as shown in Fig. 2.4. If one side suspension electromagnets of the overlapping structure cannot work due to the fault, the other one is still able to take the suspension function of suspension frame by the overlapping structure to avoid the falling accident.

Considering that the overlapping structure makes high-speed Maglev train have the huge lower substructure, the system's weight and complexity and the difficulty of control will increase.

2.3 Suspension Control Algorithms of Maglev Train

2.3.1 Basic Requirements of Suspension Control Algorithms

The study on suspended control algorithms of Maglev train is one of the most active topics in the Maglev technologies. Based on the structural characteristics and engineering requirements of suspension system in EMS Maglev train, some basic requirements on suspension control algorithms are listed as follows [29, 30]:

1. Good adaptability for the uncertainty of suspension system models

Whether single electromagnet or module suspension control schemes are adopted, each Maglev vehicle contains multiple suspension objects. There are large or small differences between the parameters of these objects each other, and there are also differences between the train and the train's suspension system parameters. If each suspension object is respectively designed and the control parameters are debugged, the industrialization requirements are obviously meet for Maglev train. In addition, the changes of work environment can also result in the suspension system parameters perturbation. Therefore, the suspension controller should have good adaptability for the module differences and system parameter perturbation caused by the environmental change.

2. Good robustness for the external interference of suspension system

In the operation process of suspension system, the suspension magnetic field, electromagnetic radiation of chopper, track irregularity, and other factors can cause the state fluctuation of the sensor measured signals. The change of the passenger number can also result in the load change of suspension system. Therefore, the suspension controllers should have good robustness for these two external disturbances.

3. Good suppression ability for the track coupled vibration

The suspension system consists of suspension electromagnet and track suspension. The suspension is the result of their interaction. In the laboratory environment, if the track stiffness coefficient is large enough, the track can be usually considered as a rigid body, and the elastic vibration and geometric distortion of tracks are ignored. In the actual line, the track stiffness cannot be very large. In the operation process of suspension system, the resonance between the vehicle and the track easily occurs and even causes the system to diverge. All of Germany's TR-04 system, HSST-04 system in Japan, and the US AMT systems have the suspension system failure due to vehicle vibrations of the vehicle–track coupling. Therefore, whether considering the operating safety or comfort of Maglev train, the suspension controller should have good vibration suppression for the vehicle–track coupling vibration under different conditions.

2.3.2 Suspension Control Methods of Maglev Train

In the early development of Maglev train, due to the constraints of control theory and hardware conditions, the nonlinear model of suspension system is usually expanded through Taylor series near the small neighborhood zone of work point, and the higher-order infinitesimal terms are ignored to obtain the system linear approximation model. Then the classical control theory algorithm is adopted to design the suspension system of Maglev train. The following are two disadvantages for the method:

1. The controller based on the linear approximation model has good control performance around the set work point. However, when the system is set away from the work point, the system performance will deteriorate sharply, and even the instability will occur.
2. Due to the suspension system model uncertainty, the performance of control algorithms based on the classical control theory is unsatisfactory to suppress the parameter perturbation, external interference, and vehicle–track coupling vibrations of the system.

In order to solve the first problem, the gain adjustment control method is proposed. In the operation range of suspension system, more than one work points are selected, and the multiple linear models can be obtained through the system model linearization in the neighborhood zone of each work point with Taylor series expansion method. In addition, the reasonable gain control is respectively designed for these linear models. The suspension control system can automatically select the appropriate control gain based on the current suspension state.

With the development of nonlinear science, the feedback linearization of nonlinear systems has become more mature linearization method. Utilizing the principle of differential geometry, through rigorous mathematical derivation, the linear model of nonlinear system can be obtained by using nonlinear term exact offset method. The linear model obtained in this way is not only accurate, but also global, namely, does not depend on the set work point [31–33]. Considering that the feedback linearization procedure contains multiplication and square root operations, the hardware system requires high performance demand. With the development and popularization of digital controllers, the feedback linearization algorithm, which can achieve more convenient and accurate performance, has been widely used gradually in the design of the suspension control system [34–36].

With the rapid development of nonlinear system theory, modern control theory, and microelectronics technology, in order to solve the second disadvantage, more and more modern control methods and nonlinear control methods are applied to the design of the suspension control algorithm, such as optimal control, fuzzy control, neural network control, adaptive control, robust control, sliding mode control, and so on [37, 38].

These control methods are presented as follows [39–43]:

1. Optimal control method

With DSP controller, an adaptive suspension controller optimization method based on model reference is realized, which can have good inhibitory for the external force interfere and the suspended mass change in ensuring the premise tracking performance.

2. μ analysis/synthesis method

μ analysis/synthesis method can be adopted in the suspension control. Based on the different idealized assumptions for actual system, four structure models are derived. For different models, the maximum, minimum, and nominal values of the parameters are determined by means of experiments and measurements. The model with the simplest structure and the nominal value parameter in the four model structures is selected as the nominal model. The additive uncertainty is calculated, and the robust performance indicator is established to determine the frequency weight function uncertainty. The algorithm can efficiently suppress the model parameter perturbation, but the choice of the nominal model is more difficult, and the realization of control algorithm is more complex.

3. Robust control method

For the cascade control method of suspension system, the suspension system is decomposed into the two subsystems with current loop and position loop [29]. The robust theory is adopted to design current loop, which can well compensate the great delay caused by electromagnetic inductance. In addition, classical control theory is adopted to design the suspension controller to achieve a full-size bogie suspension.

Since the position loop is designed with classical control theory, the suppression performance for the model perturbation, external interference, and vehicle–track coupling vibration is not obvious. But the cascade control idea has generated a great deal of influence for the suspension control algorithms design.

4. Sliding mode control method

The dynamic sliding mode suspension controller can efficiently suppress the system parameter perturbation and external interference and to some extent can weaken the chattering in the static variable structure controller [44–46].

In addition, based on suspension clearance and electromagnet acceleration signals, through the obtained damping signals from robust state observer, the stable single bogie suspension of Maglev train can be realized with the design suspension controller, which can solve the vehicle–track vibration problem of Maglev train to some extent [47–49].

At present, there are many new suspension control algorithms. Some algorithms have been applied in the laboratory experiment verification, and more still remains in the simulation stage [50–52]. The algorithm effectiveness still needs to be verified in practical engineering applications [53–59].

2.4 Conclusion

Maglev control technology has been widely used and rapidly developed. In this chapter, from the applications of low-speed Maglev train and high-speed Maglev train, the applications for Maglev control technical analysis are introduced [60–63]. In addition, Maglev control technology involves a number of research areas. The summary is not comprehensive and complete. It is hoped to provide some help for Maglev control technology research.

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