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Review

Control Methods for Levitation System of EMS-Type Maglev Vehicles: An Overview

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Abstract: As new advanced vehicles, electromagnetic suspension (EMS)-type maglev trains have received wide attention because of their advantages such as high speed, no mechanical friction, low noise, low cost and energy consumption, strong climbing ability, and green environmental protection. The open-loop instability is one of the key points and difficulties for the levitation control systems of maglev trains. The closed-loop feedback control method must be applied to realize stable levitation. However, there are currently many levitation control methods just in theory. Considering their advantages and disadvantages, it is a major demand for maglev trains to select efficient, stable, applicable, and cost-saving methods to improve their dynamic performance and safety, which motivated this review. First, the current status of research on maglev trains is introduced in this paper, including types, system components, and research modes in various countries, followed by an analysis of the levitation control methods for EMS-type maglev trains. Then, the technical characteristics of the levitation control systems are described according to the basic principles of levitation systems, model building, mathematical derivation, and control objectives. Next, three kinds of typical levitation control methods are reviewed, namely, linear state feedback methods, nonlinear control methods, and intelligent control methods, according to their improvements and applications. Lastly, we summarize and evaluate the advantages and disadvantages of the three methods, and future developments of levitation control are suggested.

Keywords: EMS maglev train; magnetic levitation; linear control; nonlinear control; intelligent control

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1. Introduction

The rapid development of railway transportation has shortened the distance between people in time and space, improved the way people travel, and greatly contributed to social progress and economics. As one of the types of railway transportation, magnetic levitation (maglev) technology has been of interest to the academic community since the 1960s. Germany, Japan, the United States, China, Brazil, and South Korea have carried out research on maglev train technology, with Germany and Japan achieving research breakthroughs in terms of different technical modes because they invested in research and development earlier. China has also vigorously developed maglev transportation technology in recent years through introduction, absorption, digestion, and reinvention [1,2]. The biggest difference between maglev trains and traditional wheel-on-rail systems (high-speed train, subway, light rail, and monorail) is that there is no direct mechanical contact between the vehicles and tracks, which affects the performance of maglev trains in many aspects. Table 1 lists the differences between maglev trains and wheel-on-rail systems. Because maglev trains have no wheels, there is no mechanical contact between the carriage and the track, making operation frictionless. Although they are currently more expensive to build, they have lower operating costs, maintenance costs, and energy consumption, a longer service life, higher average operating speeds, and safer and more comfortable operation, and they can complement the fault line between aviation and ordinary and high-speed railways. They are relatively quieter because they run frictionlessly. They also have a faster start and greater climbing capacity (up to 10%), thus enabling more flexible route selection, which allows for a reduced footprint without adding a new environmental burden. These advantages make maglev trains a strong contender in the field of rail transport [3–7].

Table 1. Comparison of maglev trains and wheel-on-rail systems [8,9].

Performance	Maglev Train	On-Wheel-Rail Systems
Speed domain	· Medium–low speed: 80–200 (km/h) · Medium speed: 200–400 (km/h) · High speed: 400–1000 (km/h)	· High-speed trains: 250–350 (km/h) · Subway: 30–60 (km/h) · Light rail: 40 (km/h) · Monorail: 20–35 (km/h)
Maintenance	1.2% of the total investment	4.4% of the total investment. Periodic replacement of wheels, gear, rails, etc.
Noise	No mechanical contact 60–65 (dB)	Contact between wheels and rails, 75–80 (dB)
Curve	In 30 (m) in radius	In 150 (m) in radius
Grade	About 80–100/1000	About 30–50/1000
Safety	No possible derailment	Derails from minor defects
Specific energy consumption	45–54 (Wh/pl/km)	48.5–59 (Wh/pl/km)
Cost of construction	High	Low
Energy consumption	Very little	Mechanical resistance and wheel–rail resistance
Service life	The life of rail is 80 years, and the life of vehicle is 35 years	The life of rail is less than 50–60 years, and the life of vehicle is 20–25 years
Mode of track change	High difficulty and cost	Simple and low cost

The basic principle of maglev technology is to levitate trains using strong suction or repulsion generated by magnets, and then applying linear motors for driving. It mainly consists of levitation, guidance, input power transfer, propulsion, and control systems [9]. According to the speed class, maglev trains can be subdivided into medium- and low-speed, high-speed, ultrahigh-speed, and astronautical-speed maglev trains [10,11]. Depending on the principle of levitation, maglev technology can be divided into electromagnetic suspension (EMS), electrodynamic suspension (EDS), high-temperature superconducting pinning levitation (HTSP), and permanent magnet- electromagnetic suspension (PM-EMS). Of these, EMS and PM-EMS are active magnetic levitation approaches, where the levitation force is controlled by some active variable through continuous or intermittent measurement of the levitation gap. EDS and HTSP maglev, on the other hand, are passive maglev approaches that do not require control of levitation forces to achieve stable levitation [10,11]. Figure 1 illustrates the specific types.

Different countries have chosen different development strategies and technological routes according to their own national conditions [12]. Germany has long focused on the development of EMS technology; they developed the Transrapid (TR) to enter a mature stage of technology application (Figure 2 (left)). The TR train was developed from 01 to 09, reaching a maximum test speed of 550 km/h. Japan began developing maglev technology at almost the same time as Germany; however, unlike Germany, they chose to develop mainly superconducting maglev. Since the 1970s, Japan has developed the ML series and the L0 trains based on the MLX (Figure 2 (right)). China, on the other hand, started late in conducting research on maglev trains compared to Germany and Japan, whereby it introduced Germany's EMS technology in the early 21st century. However, with the strong support of the government, it has now mastered the key technologies and has opened medium- and low-speed maglev lines in Changsha and Beijing for operation. In terms of high-speed maglev, China built the Shanghai high-speed maglev transport demonstration line in 2000 using German TR08 technology, which is currently the only commercially operated EMS high-speed maglev line in the world (Figure 3 (left)). In July 2021, China's

600 km/h high-speed maglev transport system with fully independent intellectual property rights was launched in Qingdao (Figure 3 (right)).

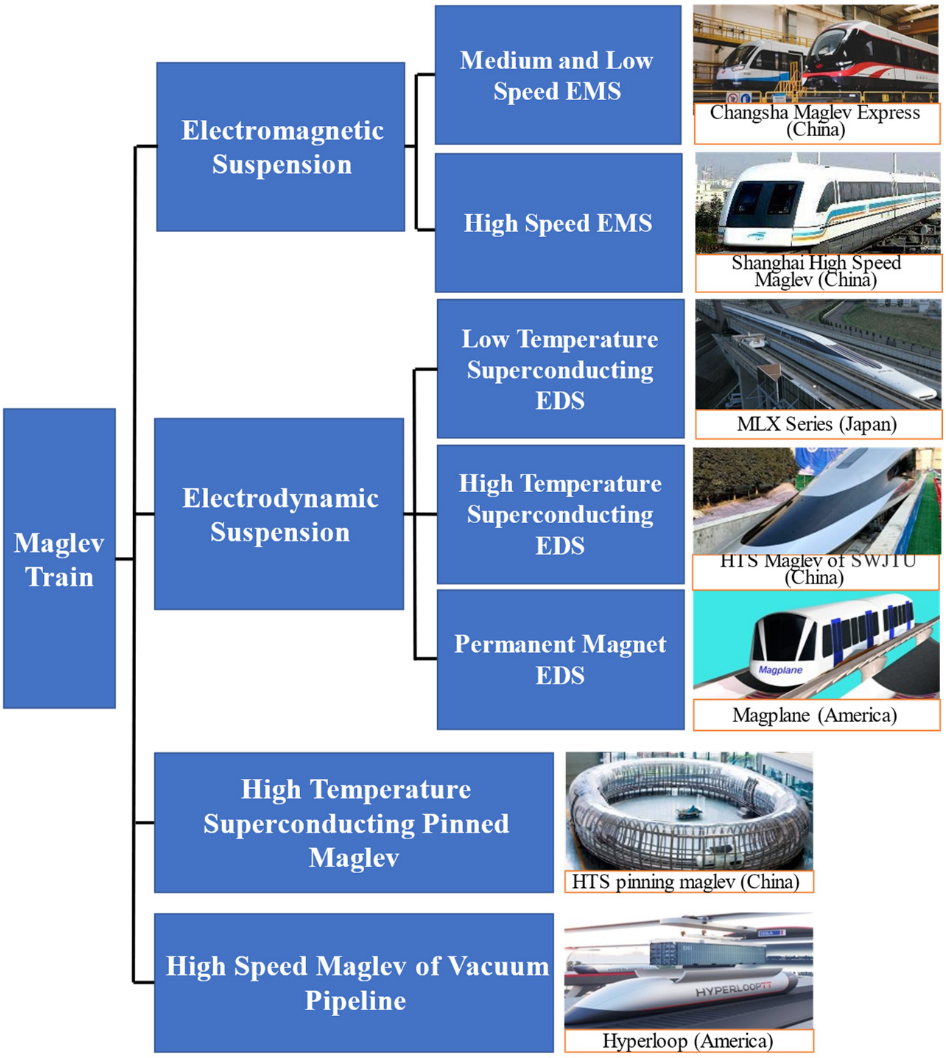

Figure 1. The types of maglev trains.

Figure 2. German TR08 Maglev train (**left**); Japanese MLX01 Maglev train (**right**).

Figure 3. Shanghai high-speed maglev train (**left**); Qingdao high-speed maglev transport system (**right**).

At present, EMS systems have been applied to a number of commercial lines, such as Linimo Line in Japan, Transrapid system in Germany, EcoBee Line in South Korea, Line S1 in Beijing, Shanghai Maglev Line, and Changsha Maglev Line in China, which shows that EMS maglev trains are reliable for urban commercial applications. For other types of maglev trains such as EDS, equivalent experiments and simulation are the main research focus in China at present. Japan's low-temperature superconducting scheme has not been applied in other countries, and the high-temperature superconducting maglev technology lacks substantial research progress; hence, it is necessary to strengthen the basic theory and technical application research in the future. The Magplane from the United States has unstable guidance and high energy loss. For high-temperature superconducting pinned suspension, Southwest Jiaotong University in China has only developed an engineering sample vehicle at present, while the Federal University of Rio de Janeiro in Brazil developed a test vehicle "Maglev-Cobra" and a 200 m test line in 2014. These technologies are still in the stage of laboratory development and cannot be commercialized. Therefore, this paper focuses on the levitation control systems of EMS trains under the above application background, which has more extensive and practical significance.

EMS-type maglev trains, represented by the German TR series, use sensors to measure the air gap in real time and feed the information to the control system, which stabilizes the levitation by adjusting the current of the electromagnet. This type of maglev train has a simple structure, is easy to maintain, does not require additional equipment such as a cooling system, and can achieve full contactless operation; furthermore, the technology is relatively mature. However, this mode requires the design of an active control system to stabilize the air gap within a certain value range when it is static or subjected to external excitation. The efficiency of the levitation controller is a core element of research. In addition, there are many control methods used in the levitation control system, which can be divided into linear state feedback control, nonlinear control based on modern control and Lyapunov theory, and intelligent control methods based on artificial intelligence technology and computer calculation according to according to technical difficulty. The algorithms used in the levitation control of maglev trains can be basically classified according to Figure 4. The advantages and disadvantages of these methods determine the specific background of application and situation of engineering. Therefore, in this paper, the main motivation is to study, analyze, and summarize the progress and corresponding application scenarios of levitation control algorithms in past studies.

At present, domestic and foreign scholars have conducted a series of review studies on general magnetic levitation systems [13–16], but there are few reviews reflecting the research results on the levitation control of EMS type maglev trains. In particular, reviews on intelligent levitation control, introducing the essential characteristics and complex factors of EMS-type maglev trains, have not been published publicly. With the continuous improvement of operation speed of EMS maglev trains, levitation control systems and closed-loop control law play an increasingly prominent and fundamental role in the fields of EMS maglev traffic dynamics and intelligent control, attracting more and more concern and attention. This paper can provide systematic and abundant reference materials for scholars engaged in this field, as well as provide a reference for the scientific and technological frontiers and key issues that maglev traffic engineers should pay attention to. The main contribution of this paper can be divided into two aspects:

1. Combined with the characteristics of rail transit, the levitation control system of the EMS maglev train is presented to readers in an all-round way, including the research routes, theoretical methods, and technical means of novel artificial intelligence methods. The target audience include scholars and engineers in the fields of rail transit, automatic control, and magnetic levitation.
2. The advantages and disadvantages of various levitation control algorithms for EMS-type maglev transportation are analyzed, covering specific problems such as multiple electromagnet module coupling and electromagnet–rail coupling vibration. This can guide the selection of levitation control methods under various speeds and scenes, which has more professional engineering significance.

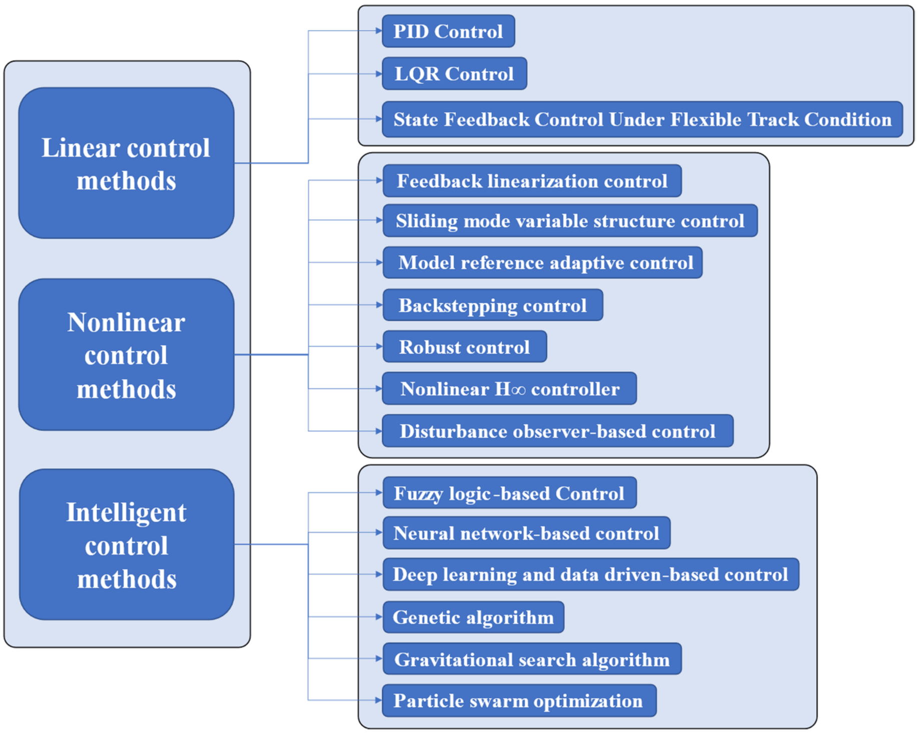

Figure 4. Classification diagram of levitation control methods used in past studies.

The remainder of this paper is structured as follows: the technical characteristics of the EMS-type maglev train levitation control system are introduced in Section 2, including the basic principles, modeling process, and control objectives. Section 3 reviews the application of traditional linear state feedback control methods. Sections 4 and 5 provide a literature review of nonlinear and intelligent control methods respectively. A comparison of the three methods is revealed in Section 6. Lastly, a summary and outlook are given in Section 7.

2. Technical Characteristics of Levitation System

The EMS-type maglev train is composed of multiple bogies, each of which has at least four levitation electromagnets. Within them, the single levitation electromagnet is the basic component [17]. Adopting the decentralized independent levitation control strategy and the modular idea of magnet structure, the control problem of the levitation system is decomposed into a single levitation control problem by decoupling, and the single magnet levitation dynamics model and dynamics characteristics are analyzed. The system of a single electromagnet consisting of a single electromagnet, its controller, and a rigid or elastic track has become the ideal model for the design of the levitation control systems [18,19]. Figure 5 shows a schematic diagram of the single-point levitation module.

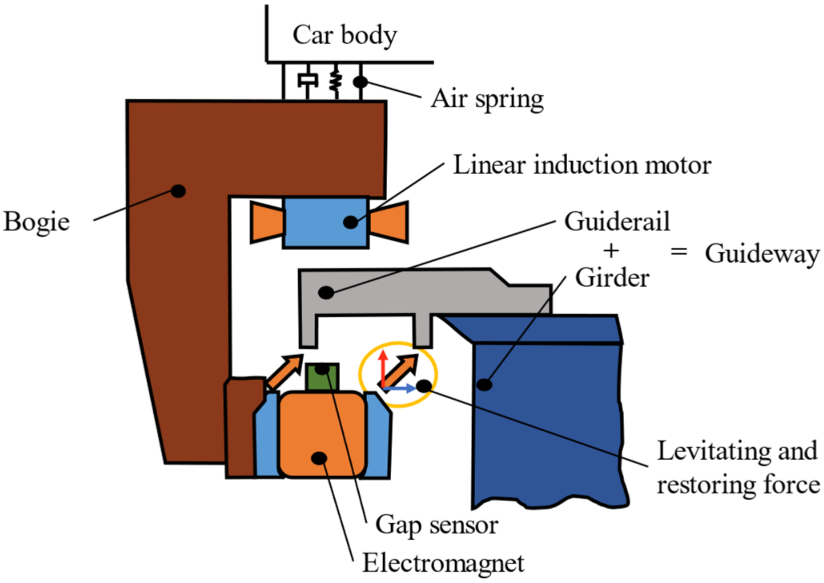

Figure 5. Schematic diagram of levitation control module of EMS-type maglev train.

The single-point levitation control system consists of a levitation frame, carriage, primary levitation, secondary levitation, electromagnet, F rail, and sensor. The levitation frame is connected by primary levitation and levitation electromagnets, whereby the load is loaded on each single levitation subsystem by the levitation frame. The attraction force is controlled by actively controlling the current of the DC (direct current) electromagnet, so that the electromagnet and the guide rail maintain an air gap of 8–10 mm to achieve levitation [20,21], and the vehicle can drive around the guide rail without contact.

The mathematical model diagram of EMS is shown in Figure 6. The levitation electromagnet and coil are under the rail. Let $c(t)$ and $h(t)$ be the displacements of the electromagnet and the track with respect to the reference plane, respectively, and $z(t)$ be the gap between the electromagnet and the track. The relationship among them is

$$c(t) = h(t) + z(t). \tag{1}$$

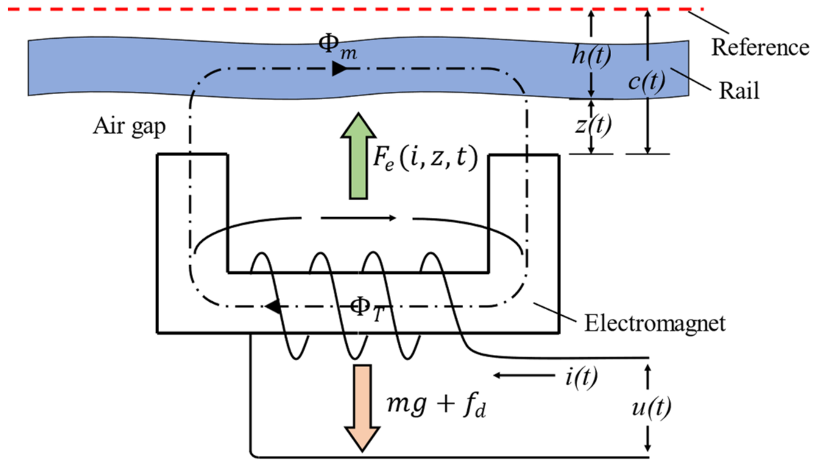

Figure 6. Mathematical model of EMS levitation system.

Ignoring the core resistance and the leakage in the air gap, the inductance of the coil can be expressed by the following equation [22]:

$$c(t) = h(t) + z(t), \tag{2}$$

where L represents the inductance, μ_0 represents the vacuum permeability, A denotes the magnetic area of the electromagnet, and N is the number of turns of the coil.

The electromagnetic attraction force between the electromagnet and the track can be expressed as

$$F_e = \frac{\mu_0 A N^2}{4} \left(\frac{i}{z} \right)^2, \tag{3}$$

where F_e denotes the attraction force, and i is the current of the electromagnet.

A more complete and detailed derivation process of the electromagnetic force equation can be obtained from [23].

Below is the voltage equation for the solenoid.

$$u = Ri + \frac{\mu_0 A N^2}{2z} \frac{di}{dt} - \frac{\mu_0 A N^2 i}{2z^2} \frac{dz}{dt}, \tag{4}$$

where u is the voltage, and R is the resistance

Taking the vertical downward as the positive direction, according to Newton's second law, the kinetic equation of the vertical direction is

$$m \frac{d^2 c}{dt^2} = -F_e + mg + f_d, \tag{5}$$

where m denotes the mass of the electromagnet, g represents the gravitational acceleration, and f_d is the interference force.

In summary, the mathematic model of the EMS levitation control system can be expressed as

$$\begin{cases} F_e = \frac{\mu_0 A N^2}{4} \left(\frac{i(t)}{z(t)} \right)^2 \\ u(t) = Ri + \frac{\mu_0 A N^2}{2z} \frac{di}{dt} - \frac{\mu_0 A N^2 i}{2z^2} \frac{dz}{dt} \\ m \frac{d^2 c}{dt^2} = -F_e + mg + f_d \\ c(t) = h(t) + z(t) \end{cases}. \tag{6}$$

If the elasticity of the track beam is not considered, i.e., $h(t) \equiv 0$, the state quantities of the system are the air gap, gap differentiation, and current, i.e., $\mathbf{X} = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix}^T = \begin{bmatrix} z & \dot{z} & i \end{bmatrix}^T$. The quantity of control is the voltage, and the quantity of output is the levitation gap. Under rigid track conditions, the state space equations of the levitation control system are expressed as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ -\frac{\mu_0 N^2 A}{4m} \left(\frac{x_3}{x_1} \right)^2 + g + f_d \\ -\frac{2R}{\mu_0 N^2 A} x_1 x_3 + \frac{x_2 x_3}{x_1} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{2x_1}{2\mu_0 N^2 A} \end{bmatrix} u. \tag{7}$$

According to the state space equations, the single-point levitation control system of EMS-type maglev trains is a strongly nonlinear system [8]. In addition to achieving stable levitation, the control objectives include suppressing the electromagnet–track coupling vibration, tracking the low-frequency changes of the track within the allowable gap variation range, such as the curve and slope, withstanding the vehicle load disturbance in a large range, and withstanding the influence of external disturbance in a certain range. A reliable active control method must be adopted for the above control objectives.

3. Linear State Feedback Levitation Control Methods

To facilitate the use of the linear control method and classical control theory, and to design a simple levitation controller, the most common approach is to linearize the model at the working equilibrium point [24–26] and, on the basis of this design, the levitation controller. This method has some stability, but also limitations. The specific process is to linearize Equation (7) at the equilibrium point $\begin{bmatrix} z_0 & 0 & i_0 \end{bmatrix}^T$ through Taylor series expansion, and then obtain the following linearized differential equation for the levitation system [23,27]:

$$\begin{cases} m\Delta\ddot{z}(t) = k_z\Delta z(t) - k_i\Delta i(t) + \Delta f_d(t) \\ \Delta u(t) = R\Delta i(t) + L_0\Delta\dot{i}(t) - k_i\Delta\dot{z}(t) \end{cases}, \tag{8}$$

where, k_z, k_i, L_0 represent the air gap coefficient, current coefficient, and the inductance of the equilibrium point, respectively.

$$\begin{aligned} k_z &= \left.\frac{\partial F}{\partial z}\right|_{(z_0,0,i_0)} = \frac{\mu_0 N^2 A {i_o}^2}{2{z_0}^3} \\ k_i &= \left.\frac{\partial F}{\partial i}\right|_{(z_0,0,i_0)} = \frac{\mu_0 N^2 A i_o}{2{z_0}^2} \\ L_0 &= \frac{\mu_0 N^2 A}{2z_0} \end{aligned}$$

The transfer function $G(s)$ can be obtained [17] by applying Laplace transform to Equation (8).

$$G(s) = \frac{\Delta Z(s)}{\Delta U(s)} = -\frac{\frac{k_i}{mL_0}}{s^3 + \frac{R}{L_0}s^2 - \frac{k_z R}{mL_0}}. \tag{9}$$

From Equation (9), it can be seen that the characteristic polynomial of the open-loop system has a positive pole and lacks terms; hence, the levitation control system must adopt closed-loop feedback control to maintain stable levitation. According to the linearized system shown in Equation (8), the traditional levitation control method is state feedback. By selecting appropriate feedback states, such as air gap, gap differentiation, acceleration of the electromagnet, and magnetic flux, the electromagnetic force is adjusted by controlling the current.

In existing EMS-type Maglev train levitation control systems, the most typical linear control method is the state feedback method [28], involving decomposition of the system into current and position loops through cascade design considerations [29–31]. Because there is inductance in the electromagnet coil, the current has a certain delay. Although the controller can calculate the required current according to the sensor, due to the influence of inductance, the current needs a certain time to apply to the levitation electromagnet [32–34]. According to the different types and application backgrounds, the linear state feedback levitation control can be divided into PID (proportional, integral, and derivative) control, linear optimal quadratic control, and linear state feedback control considering flexible track.

3.1. Levitation Control Method Based on PID

The traditional state feedback method considers various feedback quantities as the control law [23], such as position–velocity, position–velocity–acceleration, and position–velocity–flux feedback. If the current is introduced into the controller as a state quantity, a PD (proportional and derivative) controller [35–38] is adopted, and the levitation gap is taken as a feedback quantity, then we obtain a typical PD control law:

$$u = k_p(z - z_0) + k_d\dot{z} + k_c i + u_{ec}, \tag{10}$$

where k_p and k_d are the feedback control gains of air gap and gap differential, respectively. k_c denotes the feedback gain of the current, and u_{ec} represents the steady-state voltage.

Position–velocity–acceleration feedback control can be used if the chopper is used as the actuator and current is used directly as the control quantity [39–41]. k_v and k_a respectively represent the velocity and acceleration gains.

$$\Delta i = k_p(z - z_0) + k_v\dot{z} + k_a\ddot{z}. \tag{11}$$

This state feedback control method based on PID control is applicable to any model, and its simple and effective characteristics make it the most widely used in levitation control [42]. A common control block diagram of the linear state feedback method is shown in Figure 7. Many scholars have made innovations and improvements to the method on this basis. Moreno [43] used two decoupled PID controllers for a high-speed maglev train semi-bogie model to achieve bogie levitation. This method was feasible in the simulation, but it was not successfully realized in the real experiment. The reason may be that PID control was applied to the original nonlinear system after Jacobian linearization. Similarly, in order to realize the common levitation of multiple electromagnet modules of the bogie and improve the instability of magnetic pole fluctuations, Zhou [44] adopted six decoupling PID controllers for the self-designed levitation model containing six pairs of electromagnets. The least squares parameter identification method was used to identify the dynamic model parameters. However, the real system was not verified. Furthermore, independent control was adopted, without considering the strong coupling relationship between electromagnets. In this regard, a coupled MIMO (multiple-input multiple-output) magnetic levitation controller based on PID control to compensate for the effect of rotational motion was proposed by Luat [45]. He designed a force-loop controller before each sub-controller to improve stability, and then verified its robustness through experiments. However, the influence of external disturbances on levitation stability was not considered in the study. For lateral interference [46], Aly [47] conducted a comparative study of the decentralized PD controller and the centralized PD controller of the EMS system. By plotting the MIMO root locus of each controller under the conditions of system rigidity and flexibility, the gain of the two control methods was adjusted using a gradient-like search algorithm. It was seen that the centralized control could better suppress the lateral interference through the results of simulation. Figure 8 shows the control block diagram. Kim [48] predicted the disturbance force caused by the propulsion system through finite element analysis, and then designed a robust optimal levitation control method of a PID controller with internal feedback compensation using the convex optimization method. For the three failure modes caused by stable loads on the levitation frame, Wu [49] revealed the relationship between the critical speed and the PD controller gains. Parameter changes in maglev trains may be due to load variations, system resistance tolerances, improper filter use, etc., in addition to pneumatic loads. Therefore, Zhou [50] discussed several causes of electromagnetic low-frequency vibration for a single electromagnet levitation system model with a PD controller, and then proposed several methods to reduce or eliminate vibration. In order to optimize the performance of PID control, Xu [51] optimized the dynamic feedback gain system using the data of system input and output.

3.2. Linear Quadratic Regulator Levitation Controller

Although the state feedback method based on PID control is very common in EMS levitation system control, its parameter setting process is troublesome. In addition, linear quadratic regulator (LQR) control is widely used for levitation control [52–55] to improve the stability and performance. This method minimizes the cost function J by setting the weight matrix Q and R, so as to minimize the derivation and input costs. Equation (12) is the state equation and performance index function of the system. Levitation control often requires more attention to the smoothness of gap changes. Therefore, the component corresponding to air gap should adopt a larger weight. On the basis of the LQR method, some scholars have improved its application in levitation control. Li [56] adopted the LQR method in semi-active control of a magnetic levitation system. Byun [57] proposed a gain scheduling control method (GSC) based on linear quadratic Gaussian (LQG). In order to reduce the disturbance of the in-track EMS system from the LSM (linear synchronous motor) propulsion system, a new method based on LQ (linear quadratic) servo optimal control was proposed for robust control of the levitation force [58]. The results showed that the tracking performance of levitation was more stable and faster than the PID method. Park [59] built a multivariable maglev system with four inputs and four outputs on this basis. A control law that could compensate for the neglected terms was designed by applying the optimal toroidal LQ technique to each decoupled system, but the method did not take into account the system parameter uncertainty. Therefore, Sadrnia [60] added external disturbance to the system state space equation; compared with LQG control and H∞ control, the µ-frame control method was more robust.

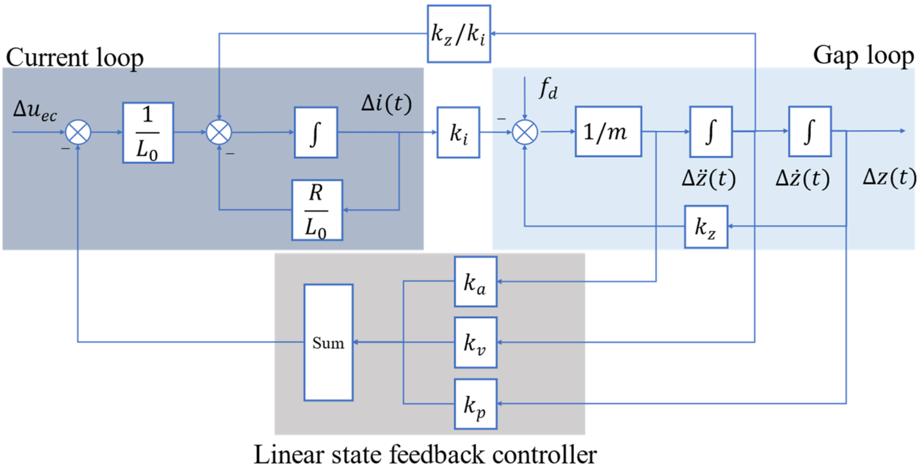

Figure 7. Linear state feedback control of EMS system (modified from [23]).

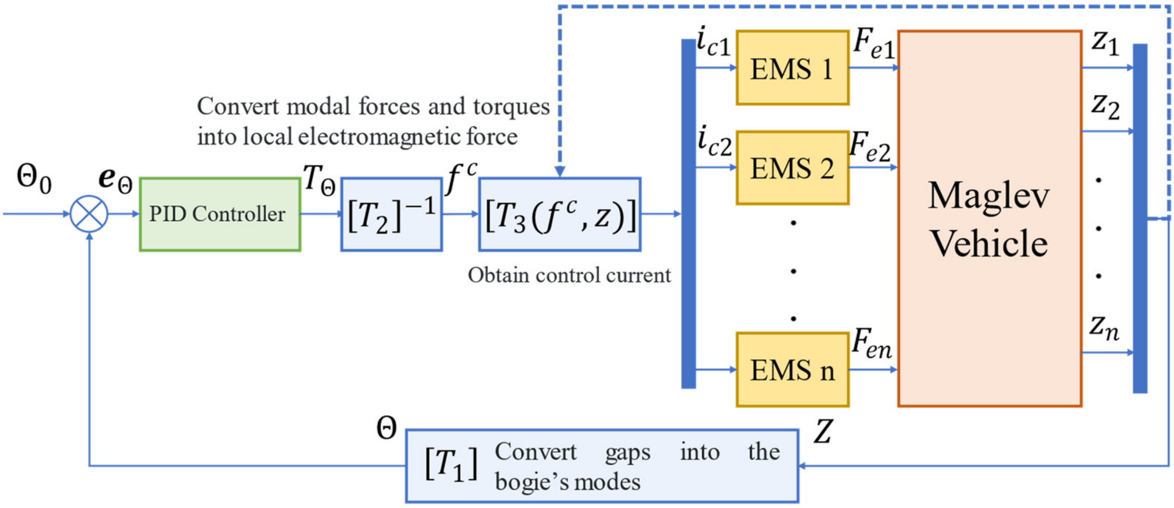

Figure 8. Block diagram of centralized PD controller (modified from [47]).

$$\begin{array}{l} \dot{x} = Ax + Bu \\ J = \frac{1}{2}\int_0^\infty \left[x^T Q x + u^T R u\right] dt \end{array} \tag{12}$$

3.3. Linear State Feedback Levitation Controller under Flexible Track Condition

Most of the state feedback controller designs outlined above treat the rail beam as rigid and ignore the vibration of the rail beam. In fact, whether it is a low- or medium-speed maglev or high-speed maglev, the coupling vibration between the train and the guideway is not negligible during the stationary or running process of the vehicle [61]. A simplified model of a coupled electromagnet–rail system is given in Figure 9. Zheng [62] performed a numerical analysis on the dynamic characteristics of the maglev vehicle on the guideway. From the results, it can be seen that the dynamics of the coupled vehicle–guide system differs from that of the uncoupled system if rail deformation is not considered. The stability and smoothness of the system are greatly influenced by the disturbance and control parameters [63]. The levitation control of the train is influenced by the irregularity, deflection ratio, local deformation [64], span length [65], etc. At very low speed, vehicle–rail resonance may even occur [66,67]. Therefore, an effective control algorithm needs to be designed for the rail vibration problem. The following Bernoulli Euler beam dynamic equation is usually used for modeling the track beam:

$$EI\frac{\partial^4 h}{\partial x^4} + C\frac{\partial h}{\partial t} + \rho\frac{\partial^2 h}{\partial t^2} = F_m(x,t). \tag{13}$$

where EI denotes the bending stiffness of the rail, h is the vertical displacement of the rail, x is the axial coordinate of the orbit, C represents the viscous damping coefficient, ρ is the mass of the rail per unit length, and $F_m(x,t)$ is the electromagnetic interaction.

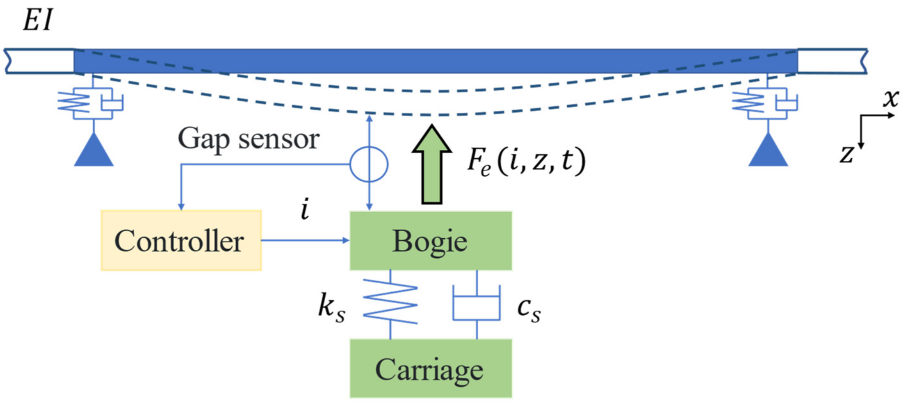

Figure 9. Schematic diagram of the electromagnet–rail coupling system (modified from [68]).

Then, the differential equation for the generalized coordinates of the modal state can be obtained through the formula of modal analysis [62,69]:

$$\ddot{q}_n + 2Y_n\omega_n\dot{q}_n + {\omega_n}^2 q_n = Q_n, \tag{14}$$

where q_n is the n-th order generalized coordinate, $\omega_n = \frac{(n\pi)^2}{L^2}\sqrt{\frac{EI}{\rho}}$ is the n-th order inherent frequency of the track beam, $Y_n = \frac{C}{2\rho\omega_n}$ represents the equivalent damping coefficient, and $Q_n = \int\limits_0^L F_m(x,t)\sqrt{\frac{2}{mL}}\sin\frac{n\pi x}{L}dx$ is the n-th order generalized force.

To suppress the coupling vibration many studies modeled the coupled system of elastic rail beam and vehicle–rail, while the dynamic characteristics, vibration characteristics, etc. were analyzed. In addition to using dampers [70–72] or adding gap sensors [73] to eliminate vibration, some authors improved the control method itself. There are still many applications of traditional linear state feedback controllers [39,74–77] in this field of research. In order to address the time-delay phenomenon in levitation control, Zhang [78,79] conducted a pseudo-oscillation analysis of Hopf bifurcation caused by the time delay of feedback variables, determined the periodic solution and direction of bifurcation, and adjusted the time delay and position–velocity–acceleration control parameters to suppress vehicle–rail vibration. However, this pseudo-oscillation analysis cannot guarantee the global behavior of bifurcation branches. On the basis of a five-dimensional model of a single electromagnet–elastic track coupled system, Hu [80] discussed the existence and stability of Hopf bifurcation. To determine the bifurcation direction and the stability of the periodic solution, the PD control parameters were used as bifurcation parameters when there was no improvement of the algorithm itself. In order to eliminate the self-excited vibration of the coupling system, Zhou [81,82] used a phase-corrected adaptive least mean square pair-cancellation algorithm (C-LMS) based on PD control. The system stability after application of this algorithm was analyzed using the harmonic balance method (HB). Self-excited vibration caused by the instability of the track modes were effectively suppressed by this method. Zhou [68] studied the amplitude characteristics of self-excited vibration on this basis and designed a PI (proportional and integral) controller to adjust the swing range of the supply voltage to suppress the amplitude of self-excited vibration to attenuate the vibration.

To achieve state feedback of unmeasurable parameters such as vibration velocity in coupled systems, The state observer is employed to estimate the vibration state of the electromagnet and the rail, and a linear quadratic optimization method is used to design the controller to investigate the effect of each parameter of the rail beam on stability [83]. However, since the controller is designed according to Riccati's equation, it is less robust and slower to compute. Parameter problems are hard to solve. Therefore, some scholars have studied how to improve the problem. The instantaneous optimal control algorithm was used by Li [84] to determine the specific values of the control parameters. This method is used not to obtain the global optimal index in the whole process, but to obtain the local optimal index at any time, avoiding solving Riccati equations, which can achieve rapid calculation in engineering applications. Combining the vibration states estimated by the state observer, Wang [85] used a linear matrix inequality solution to solve the state feedback gain matrix of the system to design the controller. This method has a better secondary performance index in the simulation. However, the influence of the control parameters was not discussed, and a real vehicle test was not carried out. After the simulation analysis of the vibration mechanism of the coupled system, Zeng [86] discussed the relationship between the PD control parameters and the track beam parameters. By adjusting the parameters, it is possible to adapt to the variation of rail beam parameters in a limited range and improve the severe coupling vibration. However, the study did not consider the effect of sensor and control system delays.

The linear state feedback method is still the most simple and convenient method in the current levitation control of EMS maglev trains, but its disadvantages are also very obvious. For example, due to the linearization of the system, the control may become less effective or even lose stability when moving away from the set operating point. Moreover, in the abovementioned problems of external disturbance, imbalance of the track, and vehicle–rail coupling vibration, the robustness of this method is poor.

4. Nonlinear Control Methods

The linear control methods presented above almost always linearize the system state equation and then directly design a linear model of the controller. The obvious disadvantages are poor robustness, negligence the nonlinear characteristics of the original system, and low practicality. For a strong nonlinear system such as the EMS system, many scholars, by combining Lyapunov's stability theory (Figure 10), have directly applied nonlinear control methods in recent years, including feedback linearization [87–91], backstepping control [92], sliding mode control [93–95], adaptive control [96–98], and nonlinear model predictive control [99].

4.1. Feedback Linearization Controller

Feedback linearization control is an accurate linearization method. The linearization model equivalent to the original system is obtained through nonlinear feedback of state variables or output variables. Compared with the local linearization used in Section 3, it has stronger robustness and is widely used in levitation control. Feedback linearization methods are employed to accurately linearize the nonlinear model of the levitation system, after which state feedback methods are used to design the nonlinear control law [100]. Its common control block diagram is shown in Figure 11. In the simulation, the capabilities of anti-airgap interference and anti-load interference are obviously better than the local linearization method. The model parameters are almost impossible to obtain accurately in practical applications, and the nonlinear terms are difficult to eliminate accurately; thus, Peng [101] proposed a dynamic compensation linearization method based on the extended state observer. The system can converge to the equilibrium point even when the parameters in the controller deviate from the parameters of the controlled object; therefore, the method has strong resistance to interference, robustness, and implementability. For uncertain parameters and external disturbances, Oh [102] designed a robust approximate feedback linearization control method. By adjusting the scaling factor of the gain through external disturbances, the final boundary of the state quantity can be arbitrarily reduced, such that all states of the controlled system remain bounded. Experiments were carried out on EMS. However, the system effectiveness was only determined using experiments on electromagnetic ball position control, not on maglev trains. Similarly, Pandey [103] adopted the feedback linearization control method for the levitation ball system, obtained a change matrix through the control input, and calculated the external input using the optimal algorithm. According to Lyapunov–Krasvoskii's theory, the stability of the system was proven, but it was also not tested on or applied to maglev trains. For the unmeasured parameters in the system, Afshar [104] used three nonlinear Kalman filters to estimate the uncertain mass of the train, and then used the feedback linearization method and the optimal LQR to ensure the stability and robustness of the levitation system.

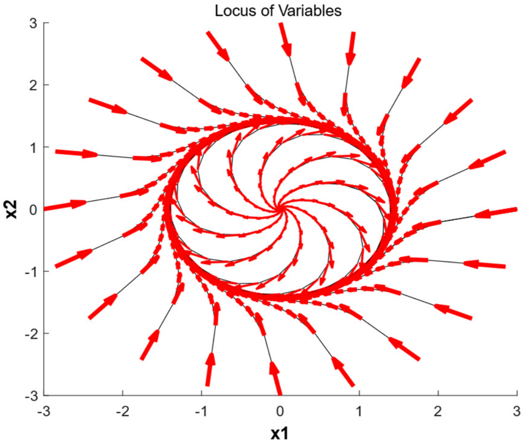

Figure 10. Trajectory diagram of variables under Lyapunov stability.

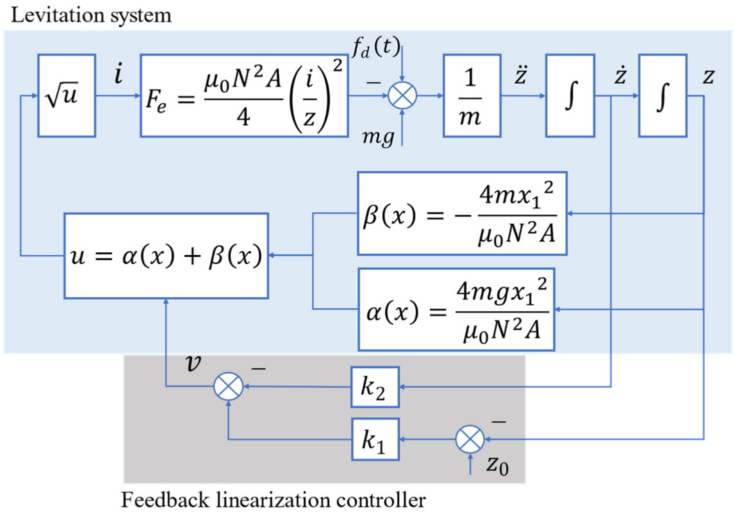

Figure 11. The block diagram of feedback linearized control (modified from [100]).

4.2. Sliding Mode Variable Structure Controller

A feature of sliding mode control is that it is independent of uncertainty and external disturbances. A decoupling sliding mode controller was proposed by Zheng [105] to address the parameter uncertainty, unmodeled dynamics, and motion coupling in the levitation module. Compared with the ordinary PID controller, this method has stronger decoupling ability. To study the dynamic response of the rail–vehicle coupling system with different speed and mass, a sliding mode control (SMC) method based on Kalman filter was proposed by Kong [106] to control the dynamic performance of the system at different specified speeds. Air gap fluctuations and vertical acceleration response were significantly reduced. Similarly, an SMC method based on nonlinear disturbance observer (DOB), comprising traditional SMC and integral SMC, was proposed by Yang [107]. A nonlinear disturbance observer (NDOB) was introduced in this method, which could estimate the disturbance in the system. A new sliding mode surface and sliding mode control law of the system under unmatched disturbance were designed, as shown in Figure 12. The buffeting problem was effectively alleviated, and the nominal performance was maintained in the magnetic levitation system. To attenuate the higher-order mismatch disturbances in the levitation system, a new continuous dynamic sliding mode control (CDSMC) method was proposed [108]. Based on the method proposed in [107], to reduce the influence of system output disturbances on the control system, a new dynamic sliding surface was established, and CDSMC rules were designed. Aimed at the time-varying disturbance of non-uniformity and load, according to the sliding mode control law, Chen [109] proposed a levitation control method by combining an acceleration feedback correction module and an adaptive compensation loop, which could control the current more smoothly under complex perturbations and significantly reduce the variation range of gap to suppress the coupling vibration.

$$\begin{cases} \dot{p} = -LB_d(p + L\eta) - L\left(\overline{A}\eta + \overline{B}_u u\right) \\ \hat{d} = p + L\eta \\ \sigma = c_1\eta_1 + c_2\left(\eta_2 + \hat{d}\right) + c_3\eta_3 \\ u = \left(CA^2B_u\right)^{-1}\left\{-CA^3T^{-1}\eta - CA^2B_d\hat{d} + {c_3}^{-1}\left[-k\mathrm{sgn}(\sigma) - c_1\left(\eta_2 + \hat{d}\right) - c_2\eta_3\right]\right\} \end{cases}, \tag{15}$$

where η is the state after coordinate transformation, including the electromagnet current, vertical electromagnet velocity, and air gap. T represents the coordinate transformation matrix, $A, \overline{A}$ respectively represent the original state matrix and state matrix after coordinate transformation, $B_u, \overline{B}_u$ respectively represent the original input matrix and input matrix after coordinate transformation, C denotes the output matrix, $B_d, \overline{B}_d$ are respectively the original disturbance matrix the disturbance matrix after coordinate transformation, $\hat{d}$ is the disturbance estimate, L is the observer gain matrix to be designed, p represents an auxiliary vector, u is the control unput, and σ is the sliding surface. The parameter $c_i(i = 1, 2, 3)$ is calculated by pole assignment, and k is the control parameter.

4.3. Model Reference Adaptive Controller

The adjustment of the state feedback parameters in traditional levitation control often requires high cost of time and labor, and the original parameters may not keep the levitation stable in the event of sudden interference. Therefore, adaptive control provides an idea of using the parameter adaptive adjustment mechanism, which is also widely used in levitation control. The reference model, the controlled object, the controller, and the adaptive controller form the model reference adaptive system (Figure 13). The position parameters of the controlled object and the feedback controller with adjustable parameters, which are controlled by the outer loop, constitute the inner loop. The adaptive regulation mechanism is the core problem of this control method. The first priority is to ensure that the controller is stable and converges quickly enough. By deriving an explicit relationship between the performance criterion parameters and the state feedback adaptive rules, Sinha [110] established a model reference adaptive controller (MRAC) for maglev trains and verified its effectiveness when the mass, interference force, and air gap settings were varied on a small representative test rig. However, the influence of elastic track beams was not considered. Li [111] applied a model-referenced adaptive control approach based on Lyapunov stability theory to a vehicle–track coupling model to address the effects of elastic track beams on stability and comfort. The results show that the method could adapt to changing parameters. Considering high-frequency coupled vibration, an adaptive vibration control scheme that eliminates the mixed vibration components in the feedback path was also proposed by Zhou [112], including an LMS (least mean square) tuned finite impulse response filter in the feedback. Based on the backstep method of adaptive control, a speed sensor-free levitation control scheme was proposed by Cai [113], which applies a high-gain adaptive observer to estimate variation velocity of the air gap to achieve global stability under uncertain unmeasurable states.

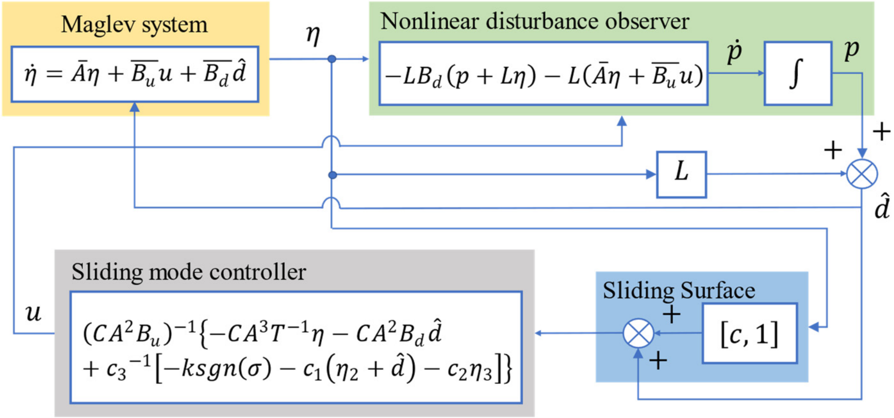

Figure 12. Block diagram of the proposed DOB based SMC method (modified from [107]).

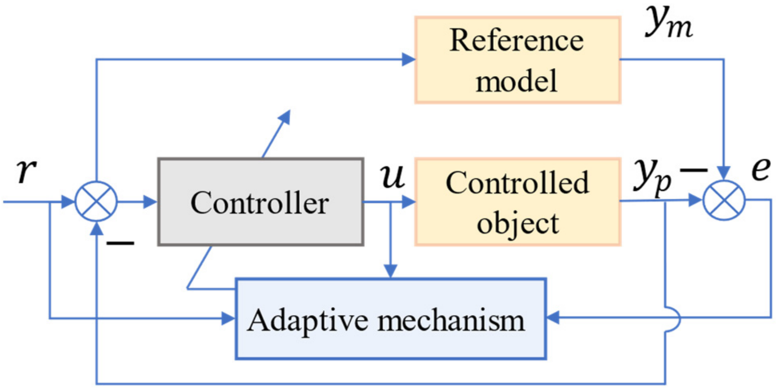

Figure 13. Model reference adaptive control system (modified from [111]).

Furthermore, some scholars have applied other nonlinear control methods to improve the robustness of EMS levitation system. For example, backstepping control (BSC) has attracted extensive attention due to its recursive design features. Backstepping control (BSC), adaptive BSC (ABSC), and adaptive dynamic surface control (ADSC) have been applied to design linear maglev systems [114]. For the problem of the Maglev train passing through the track joint, a simple backstepping controller to solve the levitation problem was designed by Wang [115], the current loop feedback was adopted, and the method was verified on a real vehicle. Compared with the traditional PID method, this method has the advantages of small overshoot, strong anti-interference ability, and fast response time in dealing with the track joint problem. Sinha [116] proposed a second-order feedback and output feedback nonlinear H∞ controller for maglev trains to improve the characteristics of interference suppression. Yang [117] proposed a new disturbance observer-based control (DOBC) method in levitation systems by appropriately designing interference compensation gain, which has better interference suppression and robustness to uncertainty than LQR plus an integral action method. Based on the improved model of levitation force, a feedback controller using FBL (feedback linearization) and feedforward controller using DOB and harmonic feedforward compensation were established by Ni [118]. The good anti-interference ability and levitation force pulsation suppression ability of the method were verified through simulation and experimental tests. Pakkhesal [119] applied the sum-of-squares (SOS) method to levitation control. This method is based on the Ratzner stability theorem and uses the convexity of the solution set through the convex optimization tool. The control input is smooth and stable in finite time. A nonlinear control method for high-speed maglev was proposed by Jiang [120] to improve the stability and comfort of high-speed maglev operation on inhomogeneous tracks, which combines a fixed time perturbation observer (FTDO) and a global finite-time controller (FTC) to accurately estimate the irregularities in the desired bandwidth For irregularity of the track, a prescribed time synchronization controller (PTSC) was designed by Jiang [121] to introduce an event-triggering mechanism for each independent levitation unit to reduce the start-up time, while incorporating two adaptive disturbance observers (ADOs) to account for input constraints.

5. Intelligent Control Methods

Computer technology and artificial intelligence technology have been gradually introduced in modern control engineering to control complex control systems. Based on traditional linear and nonlinear control methods, the introduction of intelligent technology in the levitation control of EMS-type maglev trains has opened up many new approaches. Its characteristics of self-adaptation, self-optimization, self-learning, and self-repair are used to solve the uncertainty problems of parameters and disturbances in the model. Although nonlinear control methods can be used for highly nonlinear systems such as levitation system, the results are often unsatisfactory. Therefore, many scholars, based on the linear and nonlinear control methods introduced above, have applied intelligent control theories such as fuzzy logic [122–127], neural network [128,129], deep learning, genetic algorithm, fault-tolerant control [27,130–132], gravitational search algorithm (GSA) [133], gray wolf optimization [134], particle swarm optimization, and extremum search [135] to levitation systems.

5.1. Fuzzy Logic-Based Controller

Fuzzy logic is an intelligent theory that can be applied to the control of arbitrary complex objects. It simulates the process of the human brain by making fuzzy rules and implements fuzzy comprehensive judgment, which is mainly divided into three processes: fuzzy, fuzzy rules, and defuzzy, as shown in Figure 14. The input signals are the air gap error, velocity, and acceleration, and the three fuzzy sets of positive (P), zero (Z), and negative (N) are included in the signal. Each rule corresponds to a fuzzy set of output voltage, and all membership functions are triangular or trapezoid, as shown in Figure 15. This method has been used in various ways in levitation control. For example, Yang [136] improved the PID control in the levitation controller and constructed a compound fuzzy PID controller. Compared with the traditional PID controller, this method showed faster dynamic response characteristics and better stability in simulation and experiment, but the design of the controller was established after the linearization of the levitation system. Furthermore, it did not pay enough attention to problems such as nonlinearity, interference, and mismatch. For nonlinear levitation control systems, an adaptive neuro-fuzzy SMC was proposed by Sun [137], which combined sliding mode control, adaptive fuzzy approximation, and neuro-fuzzy switching laws to address the mismatch perturbation and parameter perturbation problems. Moreover, in order to suppress external interference, based on the levitation fuzzy model with external disturbances and uncertainties, a fuzzy

H∞ robust controller based on the parallel distribution compensation (PDC) method was proposed [138], which could better adapt to the controller parameter changes. However, neither fuzzy control method took into account the vehicle–rail coupling vibration. Thus, a method combining IoT data analysis and an adaptive fuzzy controller was proposed by Sun [139]. This method extracts the control law based on the established plausible database and determines the adaptive fuzzy rules for the levitation system. However, in other nonlinear systems, the method needs to be retuned at a higher cost.

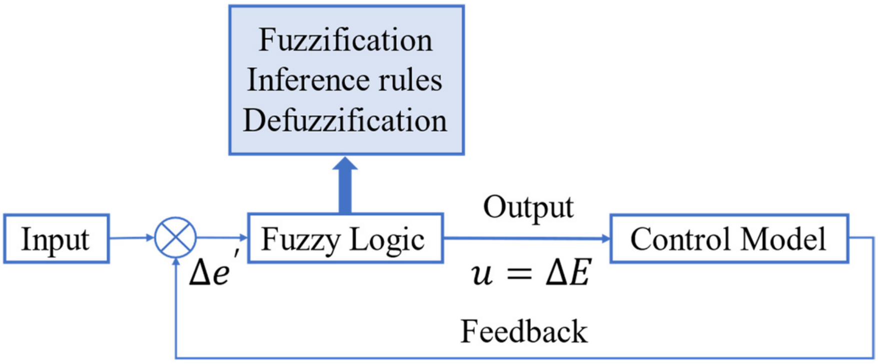

Figure 14. The block diagram of fuzzy logic control (modified from [123]).

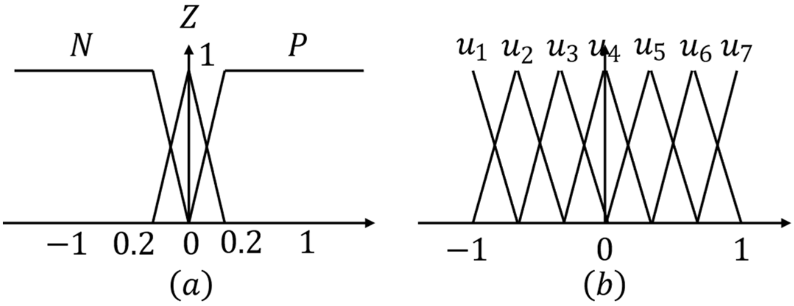

Figure 15. (**a**) Membership function of input. (**b**) Membership function of output.

5.2. Neural Network-Based Controller

The neural network is also a very popular and promising method in levitation control. It achieves the purpose of control by adjusting the interconnections between a large number of internal nodes. The structure of the RBF (radial basis function) neural network model (Figure 16) is divided into input layers, hidden layers, and output layers, where n represents the number of input nodes, and m represents the number of neurons and output nodes. The RBF vector is designed using the Gaussian function:

$$h_j = \exp\left(-\frac{\|\boldsymbol{X} - \boldsymbol{C}_i\|^2}{2{\sigma_i}^2}\right), \tag{16}$$

$$\boldsymbol{Y}_m = w_1 h_1 + w_2 h_2 + \cdots + h_m h_m = \sum_{j=1}^{m} w_j h_j, \tag{17}$$

where, $H = [h_1, h_2, \cdots, h_m]^T$ is the radial basis vector of the RBF network, $\boldsymbol{X}$ denotes the state of the system, and $\boldsymbol{C}_j = [c_{j1}, c_{j2}, \cdots, c_{jm}]$ represents the center vector of the j-th node of the network. σ_j is the base width parameter of the j-th node, $\boldsymbol{Y}_m$ is the output vector, and $W = [w_1, w_2, \cdots, w_m]^T$ is the vector of output weight.

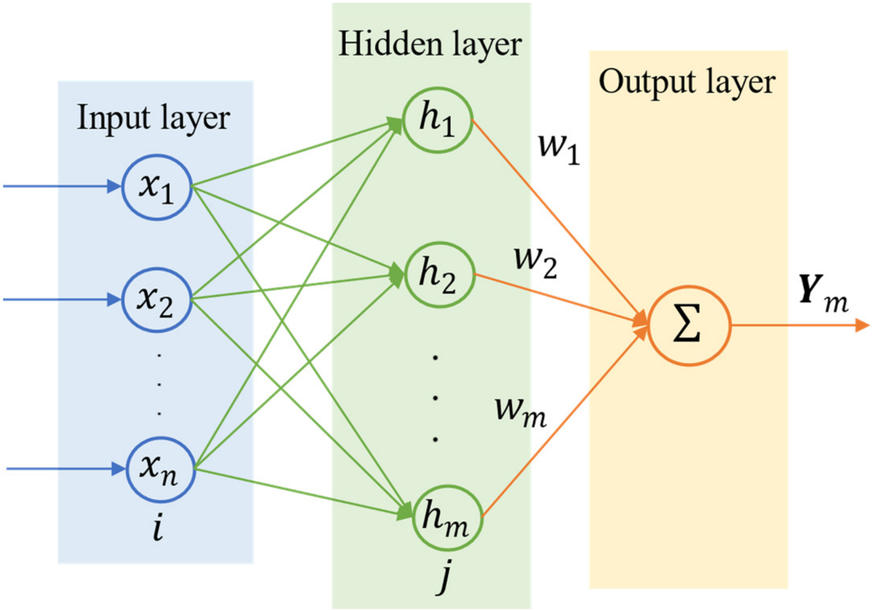

Figure 16. RBF neural network structure (modified from [140]).

On the basis of the RBF neural network structure introduced above, many scholars have designed and improved the levitation controller with nonlinear control methods. An RBF neural network modeling method was proposed by Jing [140] to solve the compensation problem of the gap sensor in levitation systems. A gradient descent learning algorithm was used to train the network to connect the model and the sensor outputs, allowing accurate estimation of the gap. However, this study did not design the levitation controller, and there was no real vehicle test. A comparison of linear state feedback control, adaptive neural network control, and hybrid control [22] was performed, while ensuring the stability and adaptability of the system using Lyapunov functions. However, the robustness was only verified on the laboratory test platform, and no real vehicle test was conducted. RBF neural networks were incorporated into nonlinear control methods and Lyapunov stability was demonstrated in [141], where time-varying masses and external perturbations could be accurately estimated in comparative simulations. Lastly, the effectiveness was verified on the single electromagnet levitation test bed, but the elasticity of the track beam was not considered in this study; moreover, it was not verified on a real vehicle. Therefore, for rail–vehicle coupling systems, an amplitude saturation controller (ASC) considering the elasticity of the track beam was proposed, and the ASC was improved using a radial basis function neural network. A neural network-based monitoring controller (NNBSC) was designed to ensure the coupling performance while solving the network time delay problem [142]. With the trend of neural network learning control, the ASC was gradually transferred to the neural network controller. The robustness in terms of time delay was verified by hardware experiments of full-size EMS-type Maglev trains. A finite-time adaptive tracking control law was proposed on that basis, which approximates the uncertainty in addressing the problems of trajectory irregularities, input delays, and time-varying quality [143]. The weights of the neural network were updated online, and the controller parameters were optimized in real time by reinforcement learning.

In terms of the application of other intelligent control methods, genetic algorithms were employed to derive the control parameters of the levitation system to optimally design the dynamic performance and weight of EMS-type maglev trains, while providing a wide range of parameters to search and find optimal or semi-optimal values [144]. This method could flexibly obtain the control parameters under different requirements. However, the levitation system was linearized and simplified, and the modeling process was rough. In order to solve the complicated tuning process of traditional PID controller parameters, Wai [145] designed a real-time PID control scheme based on the real-time particle swarm optimization algorithm (PSO-PID), which requires no auxiliary compensation controller, strict constraints, and control conversion, in addition to having better robustness than sliding mode control and fixed-gain PID control. However, this method was not verified on maglev vehicles. Aiming at the PID control parameter tuning problem, a deep learning-based PID feedback controller and deep belief network algorithm were also proposed; this method had better stability and smaller system errors in the simulation [146]. However, its adaptability to a wide range of working conditions was not tested. The extended state observer was introduced to estimate the rate of breath change in the backstepping-based output-limited controller, and a semi-supervised controller incorporating a deep belief network algorithm was proposed [147]. The deep learning controller could ensure the safety of levitation in the maglev train test. Acharya's [148] multiagent-based symbiotic organisms search (MASOS) algorithm was used for parameter tuning of one-degree-of-freedom and two-degree-of-freedom integer-order and fractional-order PID controllers for maglev devices, in which each organism acts as an agent for local interactions to calculate optimal solutions and prevent the system from falling into local optima. This provides a new idea for the intelligent levitation control of maglev trains.

Compared with nonlinear control methods that require accurate mathematical models, intelligent control has significant advantages of not requiring accurate model information and using expert experience and knowledge. However, most AI (artificial intelligence)-based levitation control strategies struggle to strictly guarantee closed-loop system stability in theory and can only be verified using simulations. In addition, for these methods, the need to readjust or relearn rules to cope with large parameter changes is inconvenient for practical applications. Stability analysis, parameter setting rules, and interpretability issues still need to be addressed in the future.

6. Discussion

According to the above analysis of the above three levitation control methods, their respective advantages and disadvantages, as well as applicable scenarios, are outlined in Table 2.

The linear state feedback method used in the early days is simple and effective in design. It only needs to introduce the output error and its differential or some state variables, before it is combined combine with the control gain parameters to obtain the control law, e.g., PD control, PID control, or LQR. These methods have a low design cost and are still widely used today. However, the disadvantages of this method are also very prominent, because the design of the controller is carried out after the original nonlinear model is linearized, and the gain cannot be adjusted online. Therefore, the effect of levitation can very easily be unstable or even unstable in serious cases, when the working state deviates from the equilibrium point, or when considering the uneven track and elasticity. In addition, some system state quantities are difficult to obtain. The tunning of control parameters also needs substantial time.

Based on Lyapunov stability theory, the nonlinear control method can be well applied to the magnetic levitation system. Currently, nonlinear control methods such as feedback linearization, backstepping control, sliding mode control, and adaptive control are used in levitation control. According to research, the nonlinear controller shows better robustness, anti-interference, and stability than the traditional PID control through comparison simulations or experiments. However, it is sometimes difficult to choose the appropriate Lyapunov function in controller design, and the complete and rigorous process of stability proof was lacking in some studies, thus increasing the complexity of the system.

With the advantages of self-optimization and self-learning, intelligent control theory has attracted more and more attention in research on levitation control. Neural network, fuzzy logic, genetic algorithm, deep learning, etc. are widely used in controller design. The characteristics of multiple modes, variable structures, and variable parameters are added to the traditional linear state feedback control and nonlinear control methods, which further improves the real-time optimization performance, anti-interference, and robustness of levitation control. However, it can be seen from the above review that many intelligent levitation control methods are still at the stage of theoretical analysis and simulation, with few test verifications and engineering applications on real vehicles; therefore, further research is needed. In addition, most modern control methods are data-iterative operations, whereby the controller is lower than the computer's main frequency, the program running cycle is longer, and the controller hardware performance requirements are higher, limiting the practical application of intelligent control algorithms.

Table 2. Comparison of advantages and disadvantages of the three control methods.

Levitation Control Methods	Advantages	Disadvantages
Linear state feedback control	· Control law is simple in structure · Mature linear theory · Strong adaptability in the static levitation stage	· As the speed increases, the accuracy of the controller decreases rapidly · The dynamic roadster stage is not robust enough · It is difficult to adjust the gain of levitation control under different environments
Nonlinear control	· Better deals with the nonlinear characteristics of electromagnetic force · Directly deals with nonlinearity under large range of air gap fluctuation · Strong robustness and anti-interference in the face of external interference	· It is difficult to select Lyapunov candidate function · The time-varying parameters of electromagnetic force are often neglected due to the high accuracy required for the model and system parameter values · The number of feedback states of the maglev system is large, and there is an unmeasurable state
Intelligent control	· Expert knowledge and experience in the maglev field can be utilized effectively · More conveniently deals with the complexity and time variability of strong electromagnetic characteristics · Addressing the complexity and uncertainty of the train operating environment, it combines the advantages of control theory and artificial intelligence technology	· Strict levitation stability proves difficult · The interpretation of intelligent levitation control algorithms is poor, and the main design process depends on experience or trial and error · The adjustment and relearning of control rules are tedious, and the efficiency of online computing is a major challenge

7. Conclusions

Levitation control algorithms have always been the focus of research on maglev trains. According to the accuracy, complexity, and intelligence of the methods, they can be divided into three categories: linear control, nonlinear control, and intelligent control methods. After analyzing the levitation control methods used in the past and their improvements, this review outlined their advantages and disadvantages, as well as their applicable engineering conditions. For example, when only static levitation is considered, a simple and convenient linear feedback controller can be applied after local linearization of the levitation system. When considering external disturbance, load change, or vehicle–rail coupling vibration, the disturbance observer, sliding mode control, and other nonlinear control methods with stronger robustness and self-adaptability can be applied. If the safety and self-diagnosis at multiple speeds need to be improved, intelligent control algorithms represent a good choice. This brings certain guidance and practical significance to the selection of maglev traffic engineering control methods.

Future research on EMS levitation control algorithms should be based on traditional state feedback, with more emphasis on nonlinear control and intelligent control, especially regarding the improvement of the ability of nonlinear control methods to deal with complexity and timely degeneration, and the improvement of the interpretability and online computing efficiency of intelligent control algorithms. In addition, controlled objects should be transferred from the strategies of decentralized and independent levitation control and modular ideas of magnets to complex models such as multi-electromagnet coupled systems and electromagnet–rail beam coupled systems, while considering issues such as time delay, network transmission, fault tolerance, and fault diagnosis in order to enhance the comprehensiveness and realism of theoretical research. Lastly, the designed levitation control methods should be evaluated on testbeds or real vehicles to verify their practicality by combining theory and practical application.

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