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Model-Based Testing Platform for Coordinated Control of Electromagnetic Suspension, Guidance, and Eddy-Current Braking in High-Speed Maglev Trains

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Abstract. The Electromagnetic Suspension (EMS) high-speed maglev system, as a representative intelligent transportation system, employs intelligent electromagnetic attraction control to achieve stable levitation above the track, enabling contactless operation and establishing itself as a next-generation sustainable transport solution. Unlike conventional wheel-rail systems, this intelligent transportation innovation addresses critical challenges including real-time system integration, automated control coordination, and multi-sensor data fusion. The development faces significant technical barriers such as extended test cycle durations, substantial infrastructure investments, and limitations in physical prototype verification for vehicular components. To overcome these constraints in controller validation and load testing for levitation stabilization, lateral guidance, and eddy-current braking systems, we developed an integrated Hardware-in-the-Loop (HIL) simulation platform aligned with Intelligent Transportation requirements. This advanced testing architecture enables comprehensive performance evaluation of coupled electromagnetic control systems across multiple operational scenarios: static levitation maintenance, dynamic trajectory tracking, emergency braking sequences, and controlled suspension release. Featuring a highly integrated architecture with modular scalability, the platform demonstrates three distinctive advantages for intelligent transportation applications: (1) Cost-effectiveness through virtual-physical system co-simulation enabling large-scale network deployment, (2) Configurable test scenario generation for multi-domain controller verification across transportation ecosystems, and (3) Accelerated test iteration cycles via real-time digital twin implementation supporting smart infrastructure evolution. Experimental validation

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confirms the platform's capability to reduce development costs by 43% while improving test efficiency by 68% compared to conventional field-testing approaches. This platform provides an essential research tool for the engineering development, operational safety assurance, and ultra-high-speed verification of EMS maglev systems within modern intelligent transportation frameworks.

Keywords. Hardware-in-the-loop simulation, maglev train, levitation controller, guidance controller, eddy-current brake controller, testing platform

1. Introduction

The EMS high-speed maglev train is the world's first high-speed maglev intelligent transportation system with a speed of 600 kilometers per hour. The levitation, guidance, and eddy current braking controllers are the core control components of the EMS high-speed maglev vehicle, and its safe and stable operation is the key to ensuring the safety and reliability of vehicle operation [1,2]. Before the levitation, guidance and eddy current brake controllers are assembled into the vehicle or after a period of use, complete fault hazard detection and performance testing are required; In particular, when the above-mentioned controller fails, it is necessary to complete fault location and maintenance with the assistance of the ground detection platform. Existing technologies for functional, performance, and fault diagnostics rely on specialized equipment such as ground test platforms, which incur high manufacturing costs and exhibit limited testing capabilities [3-5].

Hardware-in-the-loop simulation is a technology that connects the simulation model of one part of the system with the actual object of another part through the I/O interface device to complete the system simulation test, which has the advantages of shortening the R&D cycle, saving R&D costs and high confidence in the simulation results. Hardware-in-the-loop (HIL) testing can be performed for Rapid Control Prototype (RCP) verification while meeting the requirements of hardware-in-the-loop (HIL) testing [3-6]. Hardware-in-the-loop simulation technology has been widely used in the fields of UAV automatic test and tracking, aircraft attitude control, and automotive autonomous driving control [7,8]. A large number of scholars have also carried out a large number of research on the application of semi-physical technology in the field of maglev transportation. In Ref. [3], a hardware-in-the-loop simulation test platform was established for the medium and low-speed levitation control system. Ref. [4, 9-11] applied research on the application of hardware-in-the-loop simulation of high-speed maglev traction operation control system; Ref. [12,13] conducted a purely virtual simulation study on the high-speed maglev vehicle system. Ref. [14,15] studies on the application of semi-physical applications of high-speed maglev vehicle levitation systems. Based on the hardware-in-the-loop simulation technology, a special real-time simulation test platform is designed for the engineering production, testing and maintenance of levitation, guidance and eddy current braking control systems. It can carry out a comprehensive automatic test on the hardware and software functions of the entire levitation control system, greatly shorten the traditional human test cycle, greatly improve the development and maintenance efficiency of the entire suspension control system, reduce the number of physical tests, reduce the research and development costs, and will have good engineering significance.

2. Vehicle Control System

The high-speed maglev vehicle employs electromagnetic suspension (EMS) technology, utilizing electromagnet excitation to stabilize the gap between the track-mounted electromagnets and the vehicle's onboard counterparts [1]. Different from other standard trains, the core control system of the vehicle generally includes levitation control system, guidance control system, and eddy current braking control system. Therefore, building a high-fidelity virtual model of the vehicle system is the key to ensuring reliable simulation results.

2.1. Levitation Control System

Different from the medium and low-speed maglev trains, the EMS high-speed maglev train adopts a lap structure, which leads to the difference in the actual levitation control method. A lap structure is controlled by two suspension points to form the minimum levitation unit, the basic structure of which is shown in Figure 1. The minimum levitation unit consists of 2 levitation controllers and 4 levitation sensors, involving 2 levitation electromagnets [2].

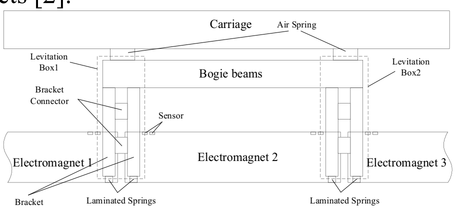

Figure 1. Levitation join-structure.

The lap structure is in fact an integral system formed by the interaction and coupling of two levitation control units and the support arm system, and the basic idea of the levitation control of this lap structure is that the lap structure is no longer divided into separate subsystems, but is modeled as a whole to realize the collaborative control of two adjacent suspension control units. The block diagram of the control loop of the lap structure under this scheme is shown in Figure 2. In addition to receiving the signals of the two suspension sensors in the circuit where it is located, the controller also needs to interact with the adjacent levitation controller, and control the levitation solenoid parts of the circuit to jointly support one air spring and its upper load to ensure that the lap structure can achieve the goal of stable levitation.

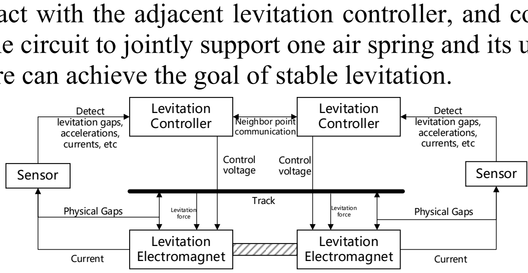

Figure 2. Levitation control loop with join-structure

2.2. Guidance Control System

In order to ensure the high-speed, stable and safe operation of the high-speed maglev train, the high-speed maglev train adopts a guidance system to exert active guiding force on the side of the train [2]. A lap joint structure is controlled by two guide points, and forms a minimum guide unit with the opposite lap structure, and its basic structure is shown in Figure 3.

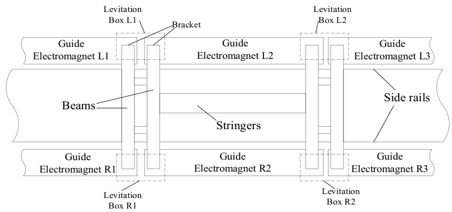

Figure 3. Guidance join-structure

As can be seen from Fig. 3, under this guide lap structure, two guide control units on the same side are not only coupled with the support arm system, but also coupled with the opposite two guide control units. The basic idea of the guided control of this more complex structure is to no longer divide the lap structure into separate subsystems, but to model it as a whole to achieve cooperative control of adjacent points and relative point differential control. The guided control loop under this control scheme is shown in Figure 4. Two guiding control loops located in the same lap structure are adjacent to each other, and the guiding control loops located on both sides of the track are opposite each other. Each guide controller receives two guide sensor signals from the circuit where it is located, interacts with the adjacent guide controller and the opposite guide controller at the same time, and controls the guide electromagnet parts of the circuit where it is located.

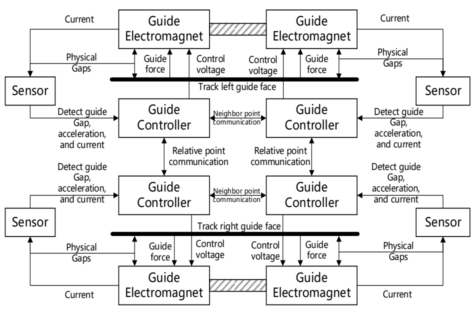

Figure 4. Guidance control loop with join-structure

2.3. Eddy Current Braking Control System

The eddy current braking system of each car is composed of 2 eddy current braking electromagnets and 8 eddy current braking controllers, forming a total of 8 eddy current braking control loops, as shown in Figure 5. Each eddy current brake electromagnets contains 12 eddy current brake poles, and each circuit contains 1 eddy current brake controller and 3 eddy current brake solenoid poles.

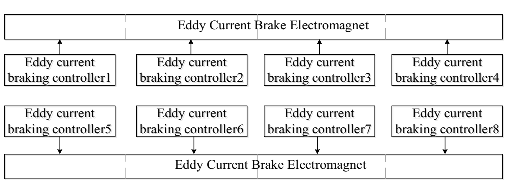

Figure 5. Eddy-current brake control system

3. Test Platform Design

Based on the characteristics of the vehicle control system of the real vehicle, the test platform adopts the overall architecture as shown in Figure 6 to meet the requirements of control loop simulation test and product dynamic test of the controller in the vehicle. The test platform is mainly composed of a test management system, simulator and model, a simulation interface platform, fault injection system, physical controller components and other test equipment.

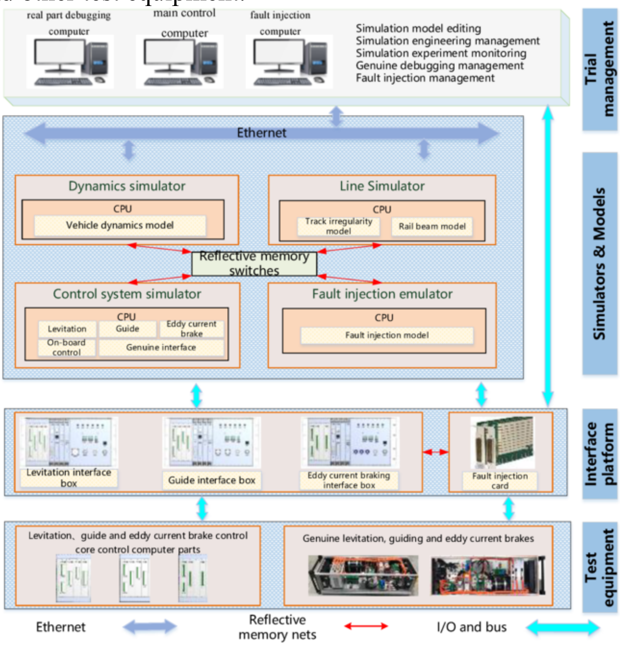

Figure 6. Platform architecture

3.1. Test Management System

The test management system is composed of the main control computer, the real part debugging computer and the fault injection computer, which can realize the functions of simulation test management, model compilation and download, simulation process monitoring, real part debugging management and fault injection test simulation. The main control computer runs RT Sim and WorkBench simulation management software. The RT Sim simulation management software generates C code from the model files established by Simulink software, such as levitation system, guidance system, eddy current braking system, and external characteristics of vehicle operation and control, and uploads them to the corresponding simulation project to complete the simulation initialization configuration. WorkBench simulation management software can import vehicle dynamics Simpack model files, establish corresponding simulation projects, and complete the initial configuration of vehicle dynamics models. The master computer runs on a Windows system environment and interacts with the emulator in real time via Ethernet. The real part debugging computer is connected to the interface platform through the CAN bus, which can receive the running status and fault information of the real controller in real time, and support the adjustment of control parameters. The fault injection computer is connected to the fault injection simulator through Ethernet, and the fault injection board can be programmed to complete the hard fault injection simulation.

3.2. Simulator and Model

The test platform uses a single-trolley frame to build the virtual model part of the platform, as shown in Figure 7. The virtual model consists of a car body, 4 levitation frames, 32 levitation controllers (hereinafter referred to as MRET), 15 levitation solenoids (hereinafter referred to as TM), 64 levitation sensors, 32 guide controllers (hereinafter referred to as MREF), 12 guide solenoids (hereinafter referred to as FM), 64 guide sensors, 8 eddy current brake controllers (hereinafter referred to as MREB), and 2 eddy current brake solenoids (hereinafter referred to as BM). The dynamic response of the car body and suspension frame was simulated by Simpack modeling. The controllers, solenoids, and sensors are modeled in Simulink. The on-board operation control, line and rail beams are also modeled using Simulink.

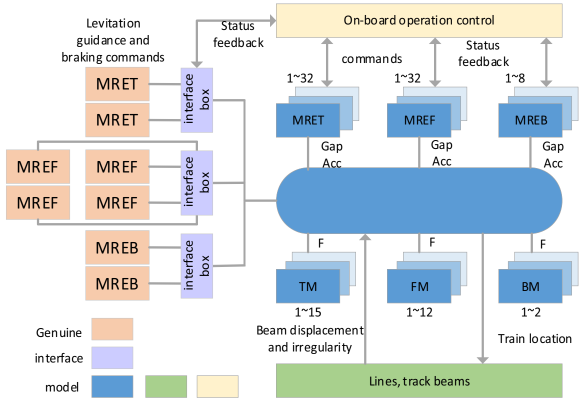

Figure 7. Virtual model

The levitation system is modeled according to the minimum suspension element, so the levitation system of a single car can be decoupled into 16 reusable minimum suspension unit models and 14 electromagnet models. The minimum levitation unit model models two adjacent hovering controllers and their sensors together, which can shield the communication between adjacent points, realize model reuse, and better improve the efficiency of model development and debugging, as shown in Figure 8 below.

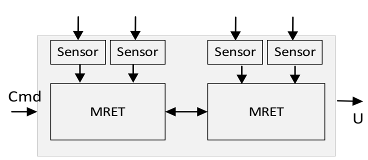

Figure 8. Minimum levitation unit model

The guidance system is also modeled according to the minimum guide element, so the platform decouples the guidance system into 8 reusable minimum guide element models and 12 guide electromagnet models. The minimum guide unit model models four guide controllers that are relatively adjacent to each other together, which can shield the adjacent want to communicate with each other, realize model reuse, and better improve the efficiency of model development and debugging, as shown in Figure 9 below.

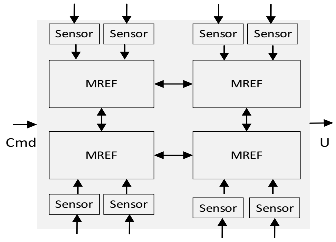

Figure 9. Guidance join-structure virtual model

The eddy current braking system for a single car consists of 2 BM electromagnet and 8 eddy current braking controllers. We model the above-mentioned models of a car together, and this structure can realize the model reuse of each car car, better improve the efficiency of model development and debugging, and reduce the data interaction between models, as shown in Figure 10.

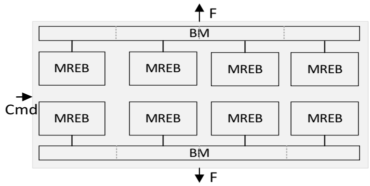

Figure 10. Eddy-current brake control system model

The platform is equipped with 4 high-performance real-time AMC simulators for Simulink model deployment and one Concurrent simulator for vehicle dynamics Simpack model deployment. The levitation, guidance and eddy current braking control system, on-board control system, wiring system and fault injection are each simulated by one AMC simulator. The AMC simulator supports high-speed PCI-e backplane buses and uses the VxWorks real-time system to meet the needs of high-performance distributed simulation. As a slave simulator, the Concurrent simulator is a Linux-based high-performance real-time computer platform that meets the demand for high computing performance for dynamic models. Each of the high-performance real-time simulators is equipped with a GE reflective memory card (PCIe-5565) and a 4-channel CAN card (PCI-CAN). The simulator is connected to the same 8-port Gigabit fiber switch via optical fiber to form a reflective memory network for real-time data communication and synchronization. The CAN card is used for high-speed communication with the real part, and the overall simulation step is better than 1 ms. Figure 11 shows the model deployment and networking

3.3. Simulation Interface Platform

As can be seen from Figure 11, the simulation interface platform is composed of a plurality of simulation interface boxes, which realizes the input and output docking with the core interface signal of the controller, satisfies the matching of signal characteristics, impedance matching and other characteristics, and realizes the hardware-in-the-loop simulation test of the real controller. The platform is equipped with 2 levitation interface boxes, 4 guide interface boxes and 2 eddy current braking interface boxes, and the actual objects of various interface boxes are shown in Figure 12. The above-mentioned interface box is equipped with 2 CAN ports, which are connected to the AMC simulator through 1 independent CAN bus, and connected to the real part debugging computer through 1 CAN bus, so as to realize the parameter configuration and status monitoring of the real part.

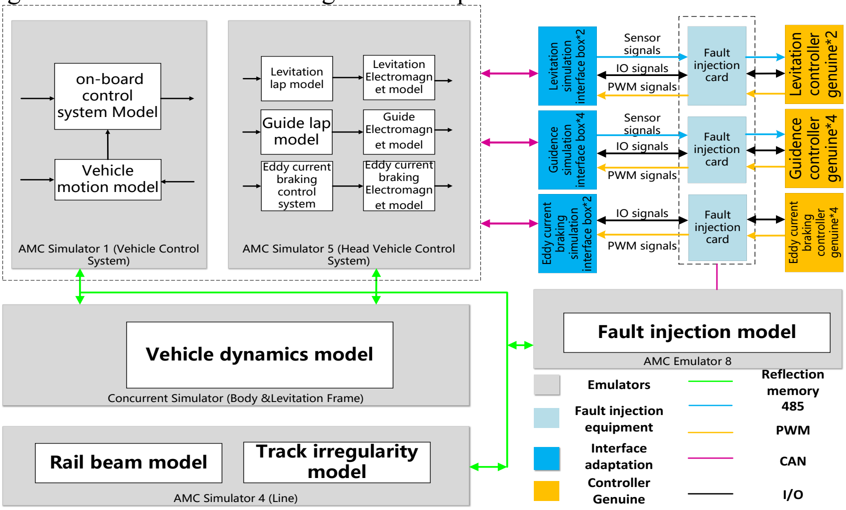

Figure 11. Model deployment

Figure 12. Levitation, guidance, and eddy-current brake controller interface box

In order to meet the requirements of the minimum levitation control unit test, a real part-in-the-loop minimum levitation unit model was also established, as shown in Figure 13. The MRET interface model runs on the AMC simulator, which delivers the model data to the interface box through an independent CAN channel and analyzes the control signals uploaded by the interface box in real time. The platform can flexibly choose to adopt the pure virtual minimum levitation unit model or the real part-in-the-loop minimum levitation unit model to meet the testing needs in different scenarios.

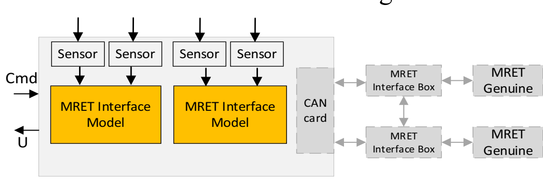

Figure 13. Levitation controller HIL test connection

In order to meet the test requirements of the minimum guided control unit, a model of the smallest guiding unit of the real part-in-the-loop was established, as shown in Figure 14. The MREF interface model runs on the AMC simulator, which delivers the model data to the interface box through the CAN channel and analyzes the control signals uploaded by the interface box in real time. In this way, we can flexibly choose whether to use the pure virtual minimum guide unit model or the real part in the loop minimum guide unit model to meet the testing needs in different scenarios.

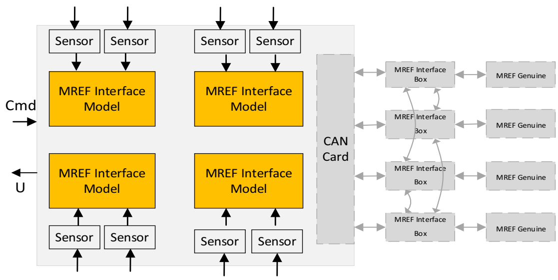

Figure 14. Guidance Controller HIL test connection

In order to adapt to the real-in-the-loop test of the eddy current braking controller, the eddy current braking system model of the real part-in-the-loop is also established, as shown in Figure 15. The MREB model replaces the MREB model with two MREB interface models, and the main function of the MREB interface model is to deliver the model data to the interface box through the CAN protocol and parse the control signals uploaded by the interface box in real time. We can flexibly choose whether to use a purely virtual eddy current braking system model or a real part-in-the-loop eddy current braking system model to meet the testing needs of different scenarios.

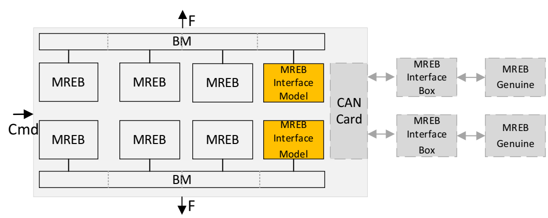

Figure 15. Eddy-current brake controller HIL test connection

4. Test Results

4.1. Test Item Point Design

Fully considering the typical working conditions of the normal conduction high-speed maglev vehicle at a speed of 600 kilometers per hour, a semi-physical simulation test platform for levitation, guidance and eddy current braking is constructed to simulate the operation of the levitation, guidance and eddy current braking system, evaluate the function and performance under different conditions, and provide visual display. We design a functional test item for the levitation, guidance, and eddy current braking system in Table 1.

4.2. Test Results

The functions of levitation, guidance and brake application and release are explained here to show the test process and test results of the test platform.

Table 1. Functions of levitation, guidance, and eddy-current brake system

NO	Function	Levitation System	Guide System	Eddy current braking system
1	Levitate Operation	√	√	
2	Load Operation	√	√	
3	Brake applied/released			√
4	Fault Diagnosis	√	√	√
5	Communication	√	√	√
6	Self-test	√	√	√
7	Fail-safe	√	√	√
8	Levitate	√	√	
9	Short-circuit Proof	√	√	√

4.2.1. Levitation controller genuine function test

(1) Test Method:

The two levitation interface boxes connected to the real parts of the levitation controller are configured as adjacent through hard wiring to form a minimum levitation unit, and the control system simulator is connected with the levitation interface box through the CAN bus; Power on the levitation interface box and configure the control parameters of the real part; Deploy and launch the test model and launch the test model; Send the levitation command to observe the model startup and static levitation state; After 30 s of static levitating , a slow landing command is issued.

(2) Test results

During testing, the same debugging software used in the actual vehicle was employed to configure parameters for the physical components, and the levitation and fault status of the real parts of the two levitation controllers were monitored in real time through the software, as shown in Figure 16. As can be seen from Figure 17, the two real levitation controllers connected to the test platform can complete the lifting and landing, static levitating and landing, and the levitation gap error of the real parts can be controlled at about 10 mm during the static levitating process.

Figure 16. Levitation controller status

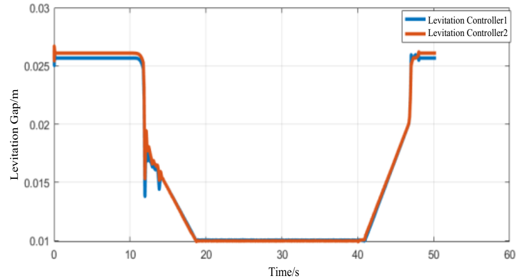

Figure 17. Levitation gap of practical levitation controller

4.2.2. Guide controller genuine guide function test

(1) Test Method:

The four guide interface boxes that are connected to the real parts of the guide controller are configured as adjacent to each other through relative and relative hard wiring, and form a minimum guide unit; The vehicle simulation system simulator is connected with the guide interface box through the CAN bus and connected to the simulation system; Power on the real guide controller and configure the parameters of the guide controller. Deploy and launch the test model and launch the test model; Send guidance instructions to observe the model startup and guidance status; After 30 s of guidance, the landing command is issued.

(2) Test results

As shown in Figure 18, the guidance and fault states of the four guide controllers are normal. As can be seen from Fig. 19, the four genuine parts of the connected guide controller can complete the process of guiding and landing, and maintain the equal guiding clearance of the left and right sides of the train, and the guidance clearance error of the four connected controllers was maintained within ±0.2 mm.

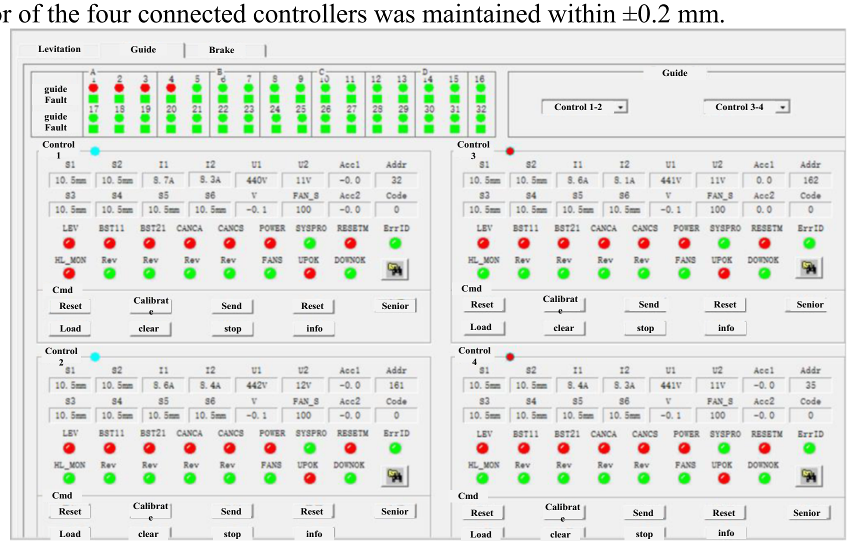

Figure 18. Guidance controller status

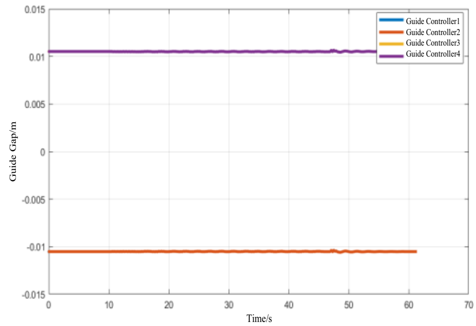

Figure 19. Guidance gap of practical guidance controller

4.2.3. Eddy current brake controller genuine brake application and release test

(1) Test Method:

Connect the two eddy current braking interface boxes connected to the real parts of the eddy current braking controller to the simulation system; The real part of the eddy current brake controller is powered on; Deploy and launch the test model and launch the test model; After controlling the train to float smoothly, the traction train accelerates to the specified speed, and then issues a 4-level braking command to observe the state of the train braking process; Before the braking is completed, the brake release instruction 0 is issued to observe the debraking state of the train.

(2) Test results

As shown in Figure 20, the braking and fault states of the two eddy current brake controllers are normal. After floating, the train accelerates according to the traction force of 80 kN, and the train has reached more than 60 km/h when it runs to 35 s, and the train issues a four-level braking command, and when the eddy current braking parts after receiving the command begin to output the control voltage to control the braking current of the BM solenoid to rise rapidly to 35.6 A. After the braking is released, the current output is cut off by the real part of the eddy current brake controller, and the solenoid current drops rapidly to 0, as shown in Figure 21.

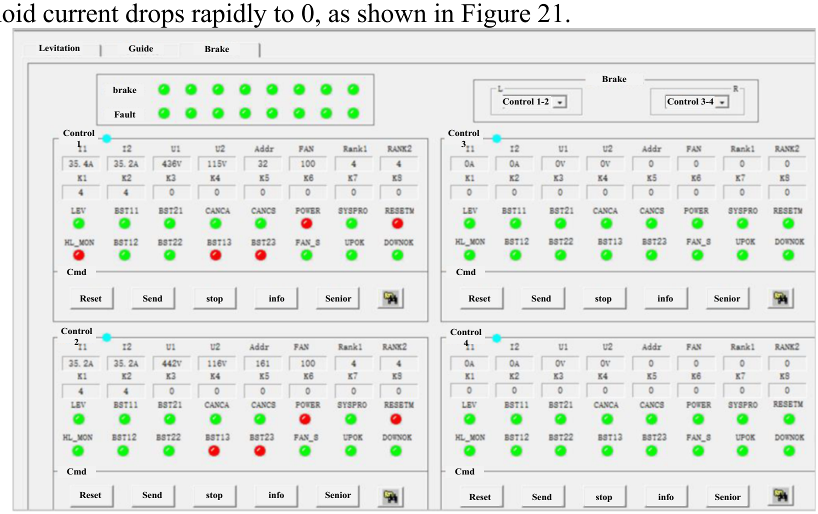

Figure 20. Eddy-current brake controller status

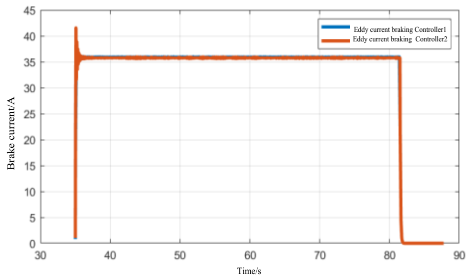

Figure 21. Output current of eddy-current brake controller

5. Conclusion

Based on the systematic analysis of the principles and components of the vehicle levitation control system, the guidance control system and the eddy current braking control system in the EMS high-speed maglev intelligent transportation system, an integrated test platform framework, test method and application case of the semi-physical simulation of the constant-conductive high-speed maglev levitation, guidance and eddy current braking controller are innovatively proposed. Replacing physical test tracks and equipment with virtual models improves testing efficiency and shortens development cycles. Compared with the all-physical test platform, the platform can be tested under different test conditions, with higher flexibility, especially suitable for controller prototype verification and controller in-the-loop testing and verification, with good application prospects, and can meet the test research and loading test needs of key components of EMS high-speed maglev intelligent transportation system.

References

[1] Kerdtuad P, and Kittiratsatcha S. Tractive Force Estimation for Hybrid PM-Electromagnetic Suspension System Maglev Train Prototype. 2020 6th International Conference on Engineering, Applied Sciences and Technology (ICEAST), Chiang Mai, Thailand, 2020, pp. 1-4.

[2] Ding S S, Eberhard P, Schneider G, et al. Development of new electromagnetic suspension–based high-speed maglev vehicles in China: Historical and recent progress in the field of dynamical simulation. International Journal of Mechanical System Dynamics, 2023, 3(2): 97-118.

[3] Isacchi G, Ripamonti F. An experimental methodology to support development of yaw damper prototypes based on a hardware-in-the-loop test bench. Vehicle System Dynamics, 2024, 62(10): 2614-2631

[4] Yaseen H M S, Siffat S A, Ahmad I, et al. Nonlinear adaptive control of magnetic levitation system using terminal sliding mode and integral backstepping sliding mode controllers, ISA Transactions, 2022, 126: 121-133.

[5] Melnikov D, Sakamoto N, Zavadskiy S, et al. Nonlinear optimal control for Maglev platform roll motion. IFAC-PapersOnLine, 2022, 55(16): 418-423.

[6] Zhu YO, Rong LJ, Zhang WY, et al. Real-time simulation for Suspension Controller Main Circuit of Maglev Train. Electric Machines & Control Application, 2022, 49(09): 50-56.

[7] Gao J, Huang Y, Song SY, et al. Hardware-In-Loop Real-Time Simulation and Test Bench for Electrical Vehicle. Transactions of China Electrotechnical Society, 2014, 29(11): 99-106.

[8] Wang RM, Zhao XM, Xu ZG, et al. Design of Virtual Simulation Test Platform Based on Vehicle-In-the-Loop for Automatic Driving. Automobile Technology, 2022(4): 1-7.

[9] Liu JX, Ge QX, Wang XX, et al. Hardware-in-Loop Research of Traction-system for High-Speed maglev. Transactions of China Electrotechnical Society, 2015, 30(14): 497-503.

[10] Li J, Xiao J, Xu J, et al. Research on Two-step-method Stator Section Crossing Control Technology for

Medium and High Speed Maglev Train. Control and Information Technology, 2021(02): 30-36.
[11] Fang K, Zhang JH, Shi YY, et al. Research on Operation Control System for High Speed Maglev with Long Stator and Normal Conducting. Control and Information Technology, 2022(01): 7-13.
[12] Zhao CX, She LH, Chang WS. Analysis of Join-structure Influencing on Guidance System for High-speed Maglev Train. International Conference on Mechanic Automation and Control Engineering, Hohhot, 2011, 7: 3855-3859.
[13] Wu YF. EMS high-speed maglev train guidance control system and its simulation. Journal of Heilongjiang University of Science and Technology, 2006(04): 244-247.
[14] Xiong ZJ. Study on Test Platform Integrated Simulation System for High-Speed Maglev. Computer Knowledge and Technology, 2010, 6(22): 6290-6291+6301.
[15] Kwak M K, Lee J H, Yang D H, et al. Hardware-in-the-loop simulation experiment for semi-active vibration control of lateral vibrations of railway vehicle by magnetorheological fluid damper. Vehicle System Dynamics. 2014, 52(7): 891- 908, DOI:10.1080/00423114.2014.906631.