Permanent Magnet Electromagnetic Hybrid Suspension System for Medium and Low-Speed Maglev Train

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ABSTRACT

The medium and low-speed maglev trains adopt EMS suspension technology. Through statistical analysis of the energy consumption data of the commercial operation line Beijing S1 maglev train, the data shows that the energy consumption of the suspension system is as high as 20%. To meet the development requirements of green, low-carbon, and environmental protection, and reduce suspension energy consumption, research on permanent magnet electromagnetic hybrid suspension technology is carried out.

Firstly, the design, structural optimization, and model establishment of the hybrid electromagnetic circuit scheme were completed. Secondly, the centralized suspension control technology based on the two in one concept has been overcome, and the suspension control algorithm based on the modular decoupling control concept has been studied. A permanent magnet anti suction control strategy and fault-tolerant control algorithm for the suspension control system suitable for medium and low-speed maglev trains have been proposed. Finally, the fabrication of a permanent magnet electromagnetic hybrid suspension system was carried out, and experimental verification was conducted on suspension energy consumption, temperature rise, and operational performance for the permanent magnet electromagnetic hybrid suspension system.

The experimental results indicate that the permanent magnet electromagnetic hybrid suspension system scheme is feasible; Compared to EMS systems, under rated load, the maximum temperature of the 24-hour static suspension electromagnet is controlled at 56 °C, reducing suspension energy consumption by 63.6%. This is a green, low-carbon, and energy-saving technical solution. This technical solution improves the adaptability of the suspension system and promotes the development of medium and low-speed maglev trains.

1. PERMANENT MAGNET EELCTROMAGNETIC HYBRID MAGNET

The permanent magnet electromagnetic hybrid electromagnet is the executing component of the control system and a key part that distinguishes it from the EMS

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system. The system needs to address issues such as suspension system safety, controllability, carrying capacity, and energy consumption.

Security requirements. The addition of permanent magnet materials can cause a suction failure between the mixed suspension electromagnet and the track. Therefore, safety requirements are a prerequisite for the design of hybrid suspension electromagnets.

Controllability requirements. The innovative use of permanent magnet electromagnetic combination in hybrid electromagnets makes the system structure more complex and the mathematical model more nonlinear, directly affecting the controllability of the suspension system. Therefore, controllability is the foundation of the design of hybrid suspension electromagnets.

Carrying capacity requirements. The hybrid suspension electromagnet can stably suspend under harsh conditions such as maximum load and maximum drop clearance.

Energy consumption requirements. To meet the requirement of reducing operational energy consumption, the hybrid suspension system reduces suspension energy consumption by more than 60% compared to the medium low speed maglev electromagnetic suspension system.

The above requirements are mutually coupled and constrained. Therefore, a finite element simulation model of the hybrid suspension electromagnet structure is established, and the design parameters are modified through simulation to determine the schematic diagram of the hybrid suspension electromagnet model as shown in Figure 1[1].

2. SUSPENSION CONTROL TECHNOLOGY

2.1 2-in-1 SUSPENSION CONTROLLER

Existing suspension controllers are generally based on single point control, and each suspension electromagnet requires two suspension controllers. To reduce weight and save costs, a 2-in-1 suspension controller has been developed, which means that each suspension electromagnet has only one suspension controller. The system has the following characteristics. Control computer, designed with dual machine hot standby redundancy function; New H-bridge power drive unit; Design the overall structure with reliability as the guide, taking into account requirements such as dust prevention, waterproofing, heat dissipation, and electromagnetic compatibility. The physical picture is as follows in Figure 2.

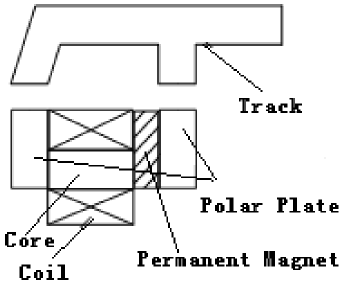

Figure 1. Schematic Diagram of Hybrid Suspension Electromagnet Model

Figure 2. Physical Picture of the 2-in-1 Suspension Controller

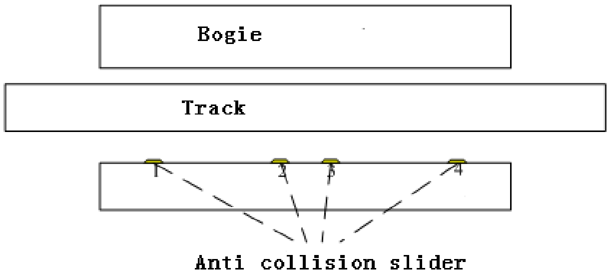

Figure 3. Schematic Diagram of the Friction Pair Structure of the Anti-collision Slider

2.2 PERMANENT MAGNET ANTI SUCTION CONTROL ATRATAGY

The anti-suction structure of the hybrid suspension electromagnet adopts anti-collision sliders, as shown in the following figure. But when suction occurs, friction will be generated between the anti-collision slider and the track, resulting in wear of the anti-collision slider. After 1-2 suction failures occur, the anti-collision slider will be worn and cannot meet the design requirements. Therefore, it is necessary to implement anti suction control strategies to prevent suction from occurring. As shown in Figure 3.

If a single point system is about to experience suction failure, reverse current should be applied in a timely manner to prevent suction failure. To avoid misjudgment caused by errors in sensor signals, a digital anti suction control algorithm with filtering function has been designed based on the characteristics of sensor gap signals:

$$k = \begin{cases} k+1 & \delta_{cgq} < \delta_{at} + \delta_{00} \\ 0 & \delta_{cgq} \geq \delta_{at} + \delta_{00} \end{cases}$$
$$u = \begin{cases} u & k < 10 \\ -u_{at} & k \geq 10 \end{cases} \qquad (1)$$

The above formula δ_{cgq} is the sensor gap value, δ_{at} the threshold gap, and δ_{cgq} the judgment basis value. (1) The formula indicates that when the sensor gap is less than the protection threshold for multiple consecutive control cycles, a negative voltage is directly output to generate the negative current required for the magnet to detach from the track. Otherwise, the control quantity is output normally.

2.3 PERMANENT MAGNET FAULT-TOLERANT CONTROL ALGORITHM

The suspension control algorithm (PIDA) based on current loop and acceleration feedback depends on the reliability of the gap sensor, acceleration sensor, and current sensor. Once several or one of the above sensors fails, the suspension control system will fail. The suspension control algorithm based on magnetic flux feedback (PIDB) utilizes gap sensor and current sensor information to estimate magnetic flux signals, and then forms a magnetic flux feedback control algorithm using the magnetic flux signals, thereby achieving fault tolerance between PIDA and PIDB algorithms. The control diagram of the closed-loop system based on magnetic flux feedback is shown in the following Figure 4 [2] [3] [4].

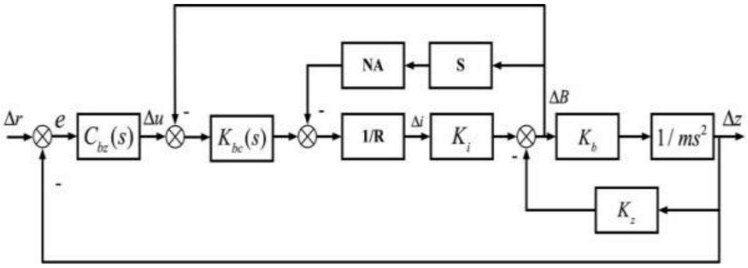

Figure 4. System Control Block Diagram

Figure 5. Mixed Suspension Control System Test Stand

TABLE I. MIXED SUSPENSION POWER CONSUMPTION TEST RESULTS

Single bogie load(T)	**Equivalent vehicle load(T)**	**Suspension gap(mm)**	**Mixed electromagnetic current(A)**	**Total power of hybrid controller(W)**	**Constant conducting electromagnetic current(A)**	**Total power of the constant conductance controller(W)**
4.6	23	9	2.1	295	25	1681
6.2	31	9	6.8	629	32	2508
7	35	9	11.9	924	36	3080

3. SUSPENSION ENERGY CONSUMPTION TEST

Based on technical research and solutions, prototype development of hybrid suspension sensors, hybrid suspension electromagnets, and hybrid suspension controllers has been completed, and a hybrid suspension control system test bench has been built. As shown in the figure below, the hybrid suspension system testing has been completed, providing technical support for medium and low-speed maglev trains, as shown in Figure 5.

The power consumption of the suspension control system is divided into two parts: the suspension power consumption of the suspension electromagnet and the power drive loss of the suspension controller. The power consumption of the suspension electromagnet can be calculated using a formula, while the power drive loss of the suspension controller needs to be measured through experiments. Under different load conditions, the total output current of the vehicle's static suspension power supply was recorded on the test bench, and the suspension power consumption was calculated as shown in the Table[5] [6].

4. CONCLUSION

The experimental results indicate that the technical solution of the permanent magnet electromagnetic hybrid suspension system is feasible; Compared to EMS systems, suspension energy consumption is reduced by 63.6% under rated load, making it a green, low-carbon, and energy-saving technology solution. This technical solution has improved the adaptability of the suspension system and promoted the development of medium and low-speed maglev trains.

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