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Design of New Energy-Efficient Permanent Magnetic Maglev Vehicle Suspension System

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ABSTRACT In view of the current traffic criticism faced by urban construction and the quality development and personalized trend of future rail transit system, a new type of maglev rail transit system is proposed in this paper. The principles of the modules of train suspension guidance, linear drive and on-board communication are also introduced and analyzed in this paper. Additionally, the feasibility of train suspension structure is studied based on Ansoft Maxwell finite element simulation, which includes: under three-dimensional magnetic field, the static magnetic force of Halbach permanent magnet array is changed, and the safety and reliability of the permanent magnet suspension array are verified by comparing with the actual test vehicle sampling data; the critical stability characteristics of suspension structure under static magnetic field are proved by physical modeling. Therefore, the electromagnetic damping structure is introduced into the vehicle suspension frame to constitute the hybrid suspension control system of permanent magnet electromagnetic, and the hybrid suspension model is established, which proves that the hybrid suspension system has controllable observability. Finally, the linearized state feedback control strategy is designed for the single-point electromagnetic levitation ball system to simulate the compensation and regulation of the static magnetic field by the electromagnetic damping system. The excellent performance of the electromagnetic levitation ball also proves the feasibility and rationality of the electromagnetic control strategy. Compared with the traditional electromagnetic hybrid suspension system, this system realizes ‘‘zero’’ power suspension, and the energy consumption of train suspension is only consumed in the instant that the electromagnetic damping system is regulated.

INDEX TERMS Medium and low speed maglev train, Halbach permanent magnet array, suspended magnetic suspension system, urban rail transit system.

I. INTRODUCTION

The problem of traffic congestion has been criticized during the development of domestic cities. With Beijing, Shanghai and Guangzhou as the typical large cities, the continuous growing scale of the cities leads to the increasingly significant contradiction between the transportation demand of urban area and the transit capacity of the traditional ground/underground transportation system, especially the traffic congestion problem. To a large extent, this reduces the efficiency and liveability of the city. At the same time, with the development of small and medium-sized cities, traffic congestion has become more and more serious. Following the publication of the National New Urbanization Plan (2014-2020), the Central Urban Work Conference and the outline of the 13th Five-Year Plan put forward a specific discussion on the construction of livable cities. After that, livable city construction becomes the important goal of our country's urban construction, and it is particularly urgent to upgrade and perfect the urban public transportation system.

Urban rail transportation is considered to be a green mode of transportation because of its large carrying capacity, safety,

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FIGURE 1. "Rainbow" rail transit system.

speed, energy and resource saving character. Research shows that the energy consumption of rail transit is only 1/9 of that of a car and 1/2 of a bus under the same capacity. Therefore, it is a common understanding of the world to give priority to the development of public transport system with rail transit as its backbone and use it as an important way to solve urban traffic problems. At present, there are seven main types of urban rail transit systems at home and abroad, such as subway, light rail, monorail, tram, maglev, etc.. The functional orientation and technical advantages and disadvantages of these systems are different, as shown in Table 1. The rail transit system like subway is mainly used to solve the problem of large volume transportation and commuting, which has been developed rapidly since the 12th Five-Year Plan. With the publication of "Opinions of the General Office of the State Council on further strengthening management of urban rail transit planning and construction", the blind construction on urban rail transit has been standardized. At the same time, with the rapid changes in the economic situation since July, there is an urgent need for the infrastructure construction, especially like railway, to exert its pull effect on the national economy. Therefore, the small and medium-sized rail transit with the goal of promoting tourism and achieving rural revitalization has been given a special mission of the times.

Suspension monorail train (also called sky train) is very popular among the cities because of the advantages of low cost, short time of construction and flexibility. It has great market potential for the development of small and medium-sized cities in the future, especially the urban areas built around the mountains, those connecting the end of the subway and residential areas, etc. Progresses in scientific and industrial technology have also promoted the rapid development of sky train. A variety of suspended rail transit systems have been put forward at home and abroad, such as the new energy suspension monorail train of CRRC Corporation Limited [1] and the BYD straddle-type Sky Rail [2], [3] in China, and the Israeli Sky Tran [4]–[6] and the Russian Sky Way rail cable car [7], [8], Germany's Dortmund Air Rail [9], Japan's Chiba Monorail [10], and so on. Among these types of sky train, most of them still use wheel-rail suspension and rotating motor drive mode, while train is devoted to the development of Personal Rapid Transit (PRT), introducing the advanced maglev technology, but the structure of it is complex. The processing of the support system is very difficult, so it is hard to be applied widely. On the other hand, the proposing of "zero" power control strategy [11], [12] promotes the development and application of the electromagnetic permanent magnetic suspension hybrid structure and the electric permanent magnet hybrid suspension structure. At present, the Maglev Research Center of Shanghai Tongji University and National University of Defense Technology has used permanent magnet array to build electromagnetic permanent magnetic hybrid suspension structure (such as Tongji University-Jiading maglev experimental line), and has successfully carried out the experiment.

Under this background, in 2014, Jiangxi University of Science and Technology proposed a new type of high-efficiency intelligent permanent magnet maglev rail transit system–"Rainbow", as shown in Figure 1 above. The system has the advantages of energy saving, environmental protection and less space occupation. It not only expands the form of urban public transportation, but also has important reference and practical application value to alleviate urban traffic congestion and enhance travel experience. Also, active research on the new rail transit system is a positive attempt to promote the transformation and the upgrading of rail transit technology, to innovate the rail transit mode, to optimize the urban spatial structure, and to protect the environment, which has important significance theoretically and practically.

TABLE 1. **Comparison on the characteristics of urban rail transit system.**

Type	Character	Technical character	Most suitable area	Price（hundred million/kilometre）
Subway	Large capacity, low energy consumption and mature technology	loud noise, high cost and long construction period	Large and medium-sized city	5-8
Light Rail	Low energy consumption and mature technology	loud vibration noise	Small and medium-sized cities, tourist areas	2.5-4
Monorail	Low noise, strong climbing ability	Dust pollution is slightly higher	Small and medium-sized cities, dedicated lines	1-4
Tramcar	Between rail transit and public transport, Flexible wiring and low cost	loud noise, greatly related to traffic volume and road right	Small and medium-sized cities, dedicated lines	0.5-1.5
EDS Maglev	Low vibration and noise, strong climbing ability, Small turning radius, little pollution	Vehicle energy consumption is slightly higher	Small and medium-sized cities, mountain cities, tourist area	3-4
Rapid Railway	Low energy consumption and mature technology	loud brake noise	Long distance suburb	2-4
Permanent Maglev Skytrain	Small vibration and noise, strong climbing ability, small turning radius, low cost and little pollution	low noise, Easy to build	Connecting airports, stations and other scenic spots to develop the new PRT traffic system	under 1

II. A NEW PERMANENT MAGNET RAIL TRANSIT SYSTEM

In this paper, a new intelligent permanent magnet maglev rail transit system named "Rainbow" is proposed, the name of which means that the system will be a smart colorful cloud over the city and contributes to the urban aerial landscape construction. The system uses the magnetic force of rare earth permanent magnetic material to realize a suspension, non-contact operation of a new air rail transit system, and it is a suspension maglev rail transit system which incorporates permanent magnet maglev, DC motor and intelligent transportation. The system has the advantages of lower building cost and lower maintenance cost, and can save more energy, protect the environment, and has less space occupation, high safety coefficient and less magnetic pollution. The permanent magnetic group made of rare earth permanent magnetic material is installed in the sky beam. The magnetic materials on the motor interact with bogies to form a repulsive force, so that the bogie and the attached car can be suspended, and driven by the long stator linear induction motor. It achieves an operation state with safety, stability, low probability to derail, reliability, and low operating noise. It has the advantages of environment friendly, strong adaptability, all-day operation, short construction time, small impact on traffic, light structure, and small area occupation. It is suitable for the low and middle volume traffic of the one-way peak section within 10,000 person / h, especially for small and medium-sized cities, tourist spots, lines around rivers and lakes, related connection lines and so on, as shown in Figures 2.

FIGURE 2. **Sample car schematic.**

For the system function, the "Rainbow" system can be divided into six modules, which are electromagnetic permanent magnet hybrid suspension control system, electromagnetic guidance control system, intelligent communication system, permanent magnet linear drive system, track and vehicle operation control system and ground power supply system.

In the suspension guide structure, the system realizes the vertical suspension of the vehicle through Halbach permanent magnet array, and realizes the real-time dynamic suspension adjustment of train safety by combining with electromagnetic stability control. There are two sets of preset suspension limit wheels at the top of the suspension frame to prevent vertical suspension collision. In the horizontal direction, the electromagnetic steering structure completes the stable control on both left and right side, and the upper and lower end of the electromagnetic guide structure are respectively installed with mechanical limit pulley to form the two-stage guide protection structure of the guide system. In addition, Secondary rubber wheels are installed on the outside of permanent magnetic levitation structure to prevent vehicle from colliding with permanent magnet array under unsteady conditions such as turning and tilting.

In the train drive system, the long stator permanent magnet synchronous linear motor is adopted. The long stator of the motor is arranged alternately by three phase AC windings, fixed on the upper wall of the inner side of the suspension beam, and the corresponding electric motor mover is composed of permanent magnets and placed at the top of the suspension frame. The traveling wave magnetic field generated by the armature winding and the static magnetic field produced by the permanent magnet forms the electromagnetic traction force and drag the suspension frame and the carriage to move forward. In the actual driving control strategy, the conventional linear motor multi-modal control method is adopted. According to the vehicle state, different driving strategies is switched to adapt the situation, including slip frequency control, vector control, direct thrust control and so on.

In order to improve the safety degree of vehicle operation and the intelligence of train service, the ‘‘Rainbow’’ system has applied the technology of Internet of Things and artificial intelligence in the on-board system. The former collects and preprocesses all kinds of field data (including levitation height, magnetic field center deviation, car body position, etc.) for the intelligent front-end system. The wireless communication equipment connects the car to the cloud control terminal to realize the exchange of data information. The latter realizes the intelligent unmanned driverless and human-car friendly interactive system of running, organizing, managing and serving. The mobile terminal can be implemented through APP, WeChat public platform and other ways to implement the operation and personalized services, which mainly include: man and machine interface interaction, traffic data display, multimedia conversion and so on, to ensure that passengers have good and comfortable experience.

In addition, the ‘‘Rainbow’’ system is equipped with the safety facilities of the conventional rail transit system, such as emergency brake button, escape ladder, smoke alarm and so on, to ensure the overall safety and reliability of the system.

To sum up, the ‘‘Rainbow’’ system is a new type of medium and low speed rail transit system with the functions of stable suspension, safety guidance, rapid driving and accurate communication. It has strong climbing ability, small turning radius and flexible driving, intelligent service and other advantages, which is suitable for small volume and scattered-mode transportation, and it has a good application prospect for the development of small and medium-sized cities in the future.

III. PERMANENT MAGNETIC LEVITATION CONTROL SYSTEM

A. SUSPENSION STRUCTURE

In the ‘‘Rainbow’’ suspension system, the ideal permanent magnet electromagnetic hybrid suspension control technology is applied, compared with the traditional electromagnetic hybrid levitation technology, its obvious advantages are: fully utilize the adaptive characteristics of Halbach permanent magnet array to achieve vehicle suspension; the electromagnetic force acts as a suspension damper to adjust the unstable disturbance under the static magnetic field in real time to suppress the vehicle oscillation. At present, both Shanghai Maglev Train and Changsha Maglev Special Line, which realize commercial operation in China, still have great energy consumption problems, especially Shanghai Maglev Train. While, Changsha Maglev Train has some improvement compared with the former in terms of levitation power consumption. But its suspension Energy consumption still accounts for about 40% of the total energy consumption of trains; in addition, the high energy consumption of trains often leads to the high cost of train operation and maintenance, which makes it difficult to promote further marketization. On the contrary, the ‘‘Rainbow’’ system uses static magnetic field to realize the suspension control of the whole structure of the vehicle. The suspension energy consumption is only generated by the electromagnetic damper, and the suspension energy consumption of the integrated train is close to zero. Moreover, electromagnetic dampers often only need to provide transient adjustment of magnetic force, so it does not need to consider electromagnetic winding heating and other problems. It also improves the service life of circuit components, and can effectively reduce the train operation and maintenance costs. It is easy to be accepted by the general public and achieve the commercialization of the ‘‘Rainbow’’ system.

According to the actual demand and simulation analysis, the engineers designed three groups of permanent magnets to form the Halbach permanent magnet array, which were laid in the suspension beam track plate and suspension frame respectively, fixed by conventional weak magnetic stainless steel (such as 304 stainless steel, Cr16Ni14 non-magnetic stainless steel), as shown in Figure 3. Limited to the progress of engineering research, two sets of suspension guide structures are set up on the suspension frame of the actual test vehicle, and the suspension and guidance functions of the vehicle are realized by connecting the rotating bearings to the suspension frame. The suspension guide module is composed of four groups of single point suspension structure and eight groups of rubber guide wheels, as shown in Figure 4. Besides, the specific parameters of the suspension structures are shown in Table 2.

TABLE 2. Parameters of "rainbow" system suspension structure.

parameter	value	unit
Monorail cross section area	4200	mm2
Double track mass per meter	61	kg
Double track magnet mass per meter	58.5	kg
Vehicle permanent magnet total length	1248	mm
Vehicle permanent magnet pole number	8	pole
Permanent magnet brand	N45H	
Permanent magnet type	simplified Halbach	
Permanent magnet height	30	mm
Design suspension height	about 10 (self-adjust)	mm
The mass of suspension frame and car	about 1.5	Ton

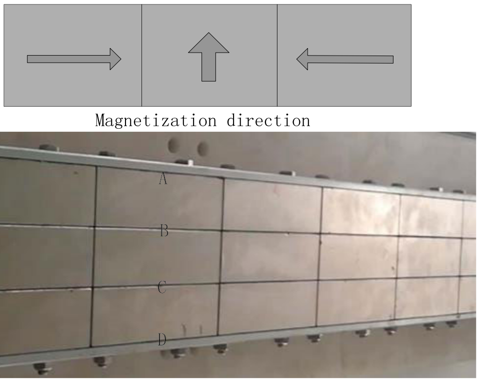


FIGURE 3. Halbach suspension permanent magnet array.

FIGURE 4. Vehicle suspension diagram.

B. STATIC MAGNETIC FIELD ANALYSIS OF PERMANENT MAGNET ARRAY

Combined with the basic structure of vehicle suspension frame, the static levitation force generated by permanent magnet array is simulated by Finite Element Method [13], [14] with the help of Ansoft Maxwell software. At the same time, combining with the actual test data, we carry out comparative verification and analysis. Because the magnetic force between Halbach permanent magnets is greatly affected by the vertical gap and horizontal offset of permanent magnet array, therefore, in the magnetic simulation analysis, we set the horizontal offset between permanent magnets as in [0-5]; In the vertical direction, the gap interval is [0-40], and six groups of sample data are used to explain it, as shown in Figure 5 below. Combined with actual project construction, in the simulation analysis of this paper, the size of the permanent magnet block is taken as 150 * 30 * 30 (corresponding to the length, width and height of the permanent magnet in figure 3 respectively). The permanent magnet adopts the sintered NdFeB N45 model. The vertical gap, the horizontal offset and the size of the permanent magnet which are described above are of millimeter magnitude (mm). The simulation data in this paper mainly focus on the analysis of the single point suspension structure without considering the coupling relationship between adjacent levitation points.

According to the above figure, the static levitation force of Halbach array and the gap and horizontal offset of permanent magnet decreases nonlinearly, and the attenuation rate of magnetic force decreases gradually with the increase of height. The levitation height of medium and low speed maglev trains in China generally are around 10 mm, while the control range of vehicle operation is stable within the controllable range of 3mm. Referring to the basic data of the medium and low speed maglev train, the static levitation force of the "Rainbow" suspension system can reach 3.33kN when the horizontal deviation is 0 mm and the suspension gap is 0 mm. The maximum load of the permanent maglev structure can reach about 1.2 Ton. When the levitation height is at 10mm, the levitation force is still 2.01kN and the maximum load is 0.12 Ton. Considering the actual engineering

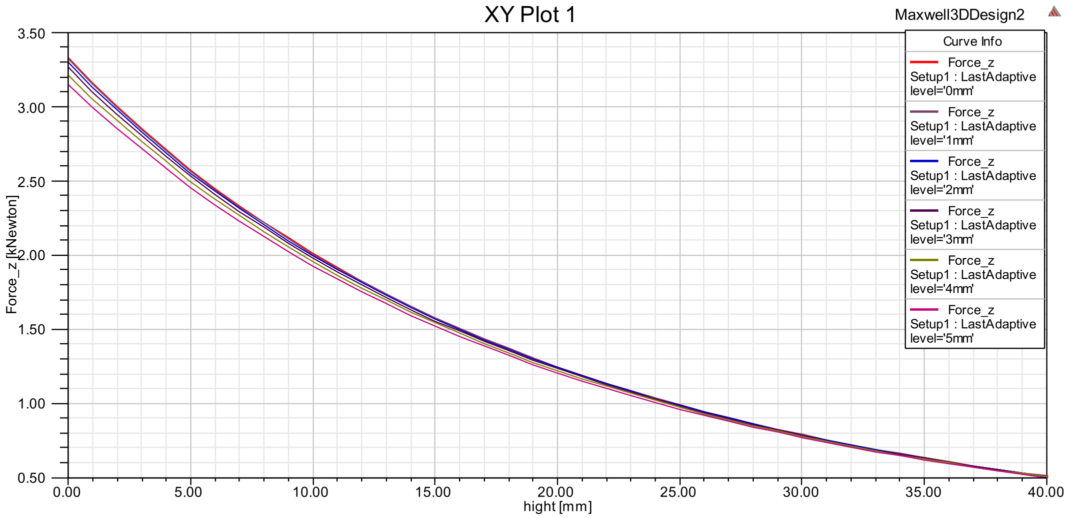


FIGURE 5. Finite element magnetic simulation curve.

TABLE 3. Suspension attenuation rates at different horizontal offsets.

Parameter category	Simple data									
vertical interval (mm)	0		10		20		30		40	
Levitation Force of horizontal offset as 0 mm and 2 mm (kN)	3.33	3.3	2.01	2.0	1.25	1.245	0.795	0.791	0.513	0.513
attenuation rate	0.9%		0.5%		0.4%		0.5%		0.06%	
Levitation Force of horizontal offset as 3mm and 5mm (kN)	3.26	3.15	1.98	1.93	1.24	1.21	0.79	0.77	0.51	0.506
attenuation rate	3.4%		2.5%		2.4%		2.5%		0.8%	

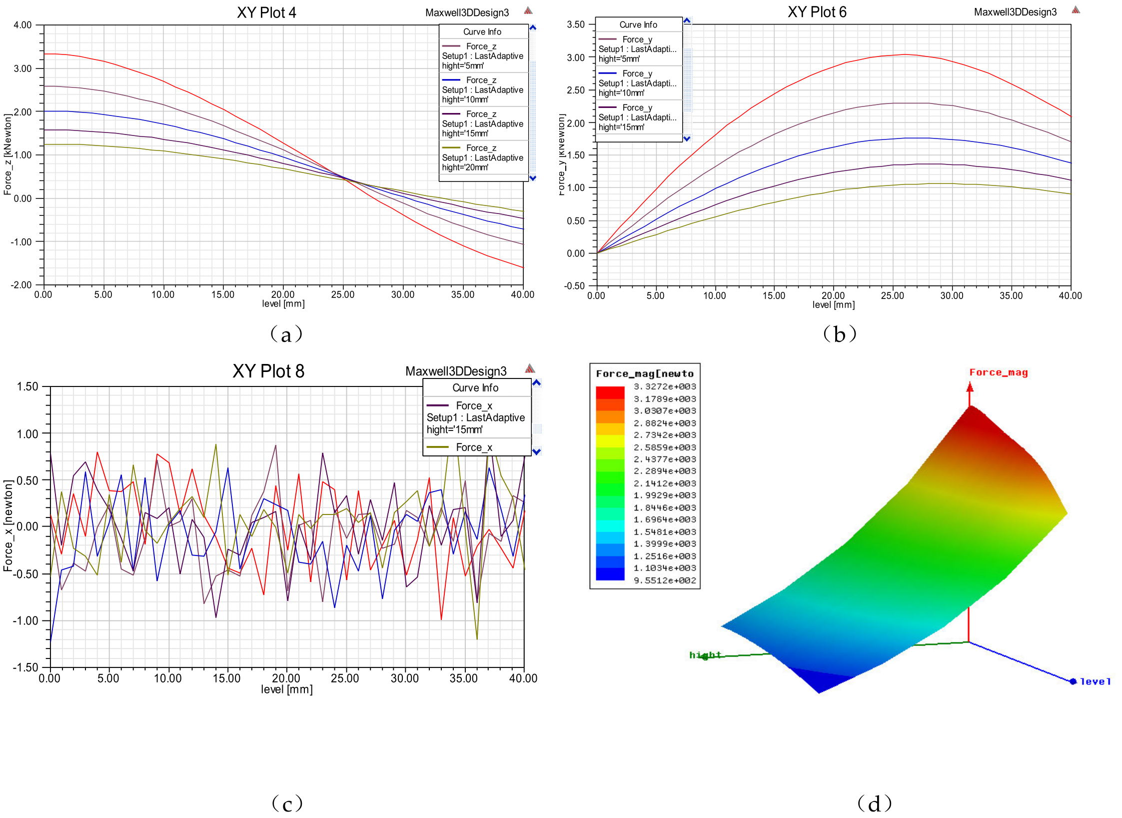
implementation, the maximum load can be maintained at about 0.5 Ton when the horizontal deviation of the train reaches 5 mm and the suspension height is 5mm. Under the influence of nonlinear factors, when the horizontal deviation is large, the attenuation of vertical levitation force is largely decreasing, which will easily cause the unstable oscillation of the system.

The effects of different horizontal deviations on the suspension force are shown in Table 3 above.

From the two groups of attenuation rate data, under two horizontal offsets condition, we can see that the vertical suspension attenuation rate shows a decreasing trend. Combined with Figure 5, the attenuation of vertical suspension force is affected by the horizontal offset obviously, such as the 10mm suspension height moment, the attenuation rate of the first group was two percentage points higher than that of the second group. This means that the effect of horizontal offset should be taken into account in the actual load design and redundant suspension design should be added. Combined with the simulation curve of static magnetic field levitation force, the influence of horizontal offset and suspension gap on 3D direction is studied and analyzed in this paper. In the figure, the levitation height range is [0-20] and the step length is 5mm. The horizontal offset ranges from 0 to 40, with a step length of 1 mm, as shown in Figure 6.

The figure shows: (a) The trend of static vertical force changes under different levitation gap conditions, (b) the horizontal magnetic force with several horizontal displacements under the levitation gap, (c) the longitudinal magnetic force along the orbital direction under different levitation gaps (d) 3D magnetic force trend with different suspension gap and horizontal offset.

In (a), when the suspension gap is in different positions, the vertical magnetic force decreases nonlinearly with the increase of horizontal deviation. When the horizontal offset is 25mm, the levitation magnetic force is almost equal, which is about 0.5 kN, and the magnetic force between magnets is repulsive. When the offset is about 30mm, the perpendicular magnetic force of the permanent magnet array is close to zero, and then increases gradually, and the magnetic direction reverses (from the original repulsive force to the attractive force), and the rate of change is different before and after



(a) (b)

(c) (d)

FIGURE 6. **Static magnetic field force curve under finite element simulation interface.**

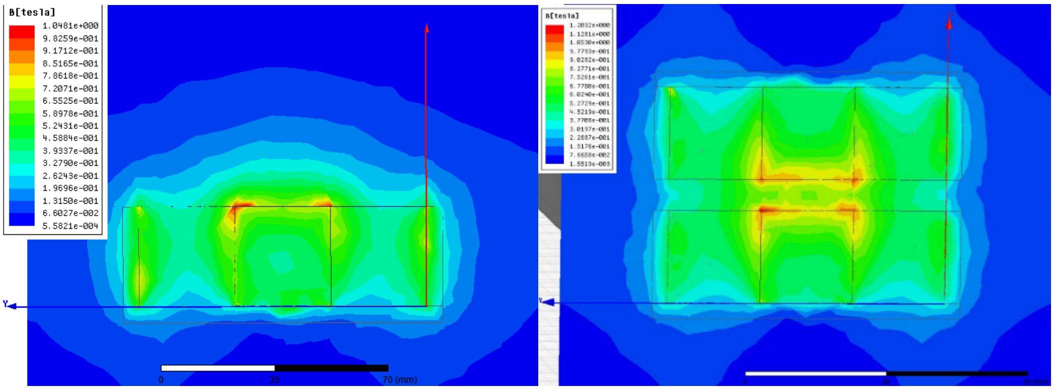
the magnetic direction flipping. That is, the magnetic suction attenuation rate is slightly smaller than the magnetic force attenuation rate. In (b), the horizontal magnetic force increases nonlinearly with the increase of horizontal offset, and then decreases gradually. The smaller the gap, the faster the magnetic growth and the larger the amplitude. The maximum horizontal magnetic force is obtained when the offset reaches about 25mm (when the suspension gap is 0 mm, the maximum magnetic force is 3.03 kN; when the suspension gap is 25mm, the horizontal magnetic force is up to 1.04 kN). It can be seen that under the ideal condition, which means the horizontal deviation is 0 mm, the horizontal steering force can realize ‘‘zero’’ power operation. When the horizontal offset is larger than 5mm, the permanent magnet array has strong horizontal lateral force, especially when the suspension gap is small, which requires the guidance control system to have strong anti-disturbance and correction ability, as well as the necessity of introducing the secondary steering structure. In (c), the amplitude of magnetic force generated by the permanent magnet array in the direction of travel along the orbit is basically zero, and will not change with the horizontal offset, but the direction is basically irregular. The influence of magnetic force along the track direction wasn’t taken into account in the actual engineering design. In (d), the horizontal offset and levitation clearance of the upper and lower permanent magnetic arrays are taken as the variable axis, and the three-dimensional integrated magnetic force (scalar) between the permanent magnetic arrays is drawn by finite element simulation. The magnetic force relationship between the gap and the offset is more intuitively reflected.

For the distribution of magnetic field intensity, as shown in Figure 7 below:

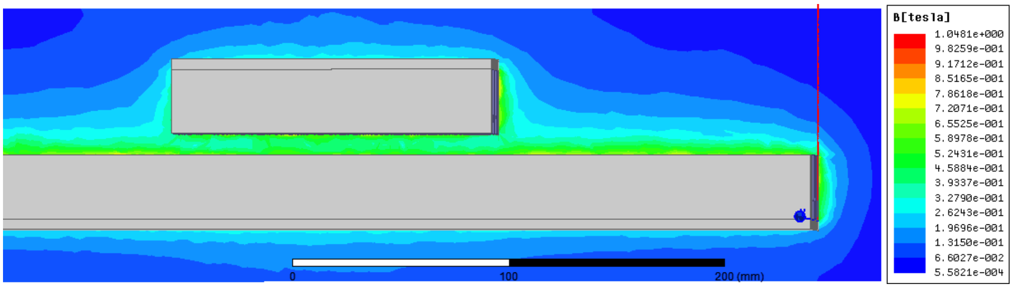
It can be seen from the diagram that the magnetic field intensity on the track line is basically concentrated on the contact surface between the Halbach permanent magnets with the maximum intensity of 1.048 kT, which is nonlinear attenuated with the increase of the distance. The magnetic field intensity between the suspension points is obviously increased. The magnetic field energy is mostly concentrated on the surface of the central magnet, and the maximum internal intensity can reach 1.8346kT. It can also be seen that the magnetic field intensity of the double layer Halbach array does not conform to the principle of magnetic field superposition.

In combination with the location of the A, B, C, D sample in Figure 3, we have carried out the field data acquisition, and the magnetic induction intensity data sample of the permanent magnet array along the track is shown in the following Table 4.

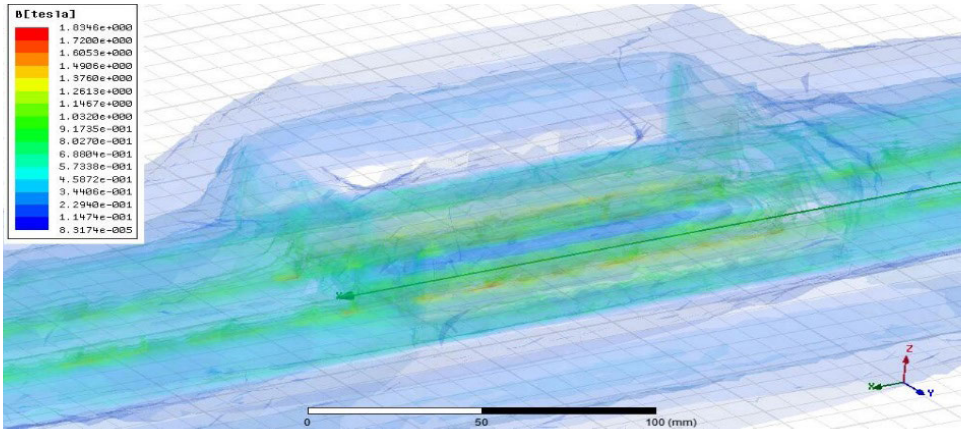
It can be seen from the sample data that the distribution of the actual magnetic field intensity is in good agreement with the finite element simulation curve. The energy of the magnetic field is distributed in the position of B and C, whose trend is high in the middle and low on the sides, and the width of the is opotential line on both sides is



(a) rail cross section (b) suspension group magnetic field cross sections



(c) permanent magnet suspension group magnetic field side



(d) Internal Distribution Map of permanent magnet suspension combined Magnetic Field

FIGURE 7. Magnetic field intensity distribution in several states.

relatively narrow, that is, the variation span of the magnetic field intensity is large. On the other hand, Figure 7 and Table 4 further illustrate that the magnetic energy of Halbach permanent magnetic arrays is basically within the centimeter level of space, The distance between the car position and the suspension module of the "Rainbow" system is more than one meter and the design height of the column is about 7.9 meters. Structurally, the magnetic energy of the suspension module is basically shielded from the beam. Therefore, for passengers in the car, pedestrians along the track of the "Rainbow" system and residents, they will not be affected by the magnetic field intensity of the permanent magnet.

C. SIMULATION DISCUSS AND STRUCTURAL OPTIMIZATION

In order to verify the simulation results, the actual test sample data are compared with the finite element simulation data, as shown in Table5. The actual data obtained the mean value of the corresponding suspension gap by increasing the load on the vehicle suspension frame.

In the above table, the actual single point bearing capacity has a certain attenuation compared with the theoretical one, but the overall attenuation rate is relatively low, which basically meets the magnetic requirements of the actual vehicle operation. The deviation rate of magnetic force at the 26mm moment of suspension gap is about 19%. Combined with

TABLE 4. **Sample data sheet of magnetic induction intensity distribution.**

Distance To The Permanent Magnet Surface (mm)	Sample Point (T)				
vertical interval	A	B	C	D	Level Interval
0	856	993	984	853	432
5	355	538	627	330	246
10	190	401	395	180	156
15	115	247	355	110	93
20	71	210	347	66	61

TABLE 5. **Simulation of suspended vertical magnetic force and practical measurement data sheet.**

suspension gap (mm)	force capacity with no theoretical deviation (KN)	real single-point capacity(KN)	capacity with no theoretical deviation(kg)	real capacity(kg)	carrying capacity deviation rate
18	1.375374	1.3475	1100	1100	2.03%
19	1.310526	1.21275	1000	990	7.46%
23	1.039977	0.94875	832	750	8.77%
26	0.9499551	0.77175	760	630	18.76%
34	0.6648323	0.57075	532	450	14.15%
39	0.5615267	0.47775	449	390	14.92%

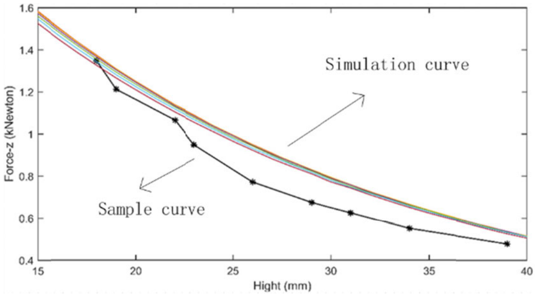
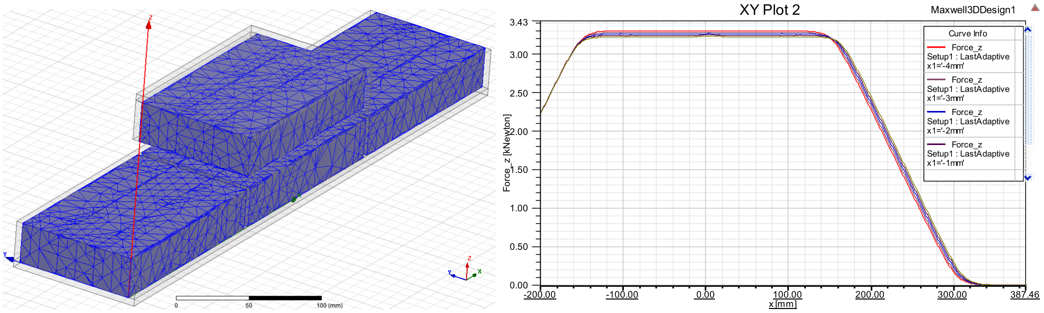


FIGURE 8. **Finite element simulation and actual measurement curve (vertical force).**

chapter C, the bearing capacity of suspension frame is not only related to suspension clearance, but also affected by horizontal deviation. Some of the sample points in Table 5 are affected by the detection position, resulting in a large magnetic deviation rate, which likely the error caused by the horizontal offset. Several sets of sample data and simulation data in Figure 5 are drawn into line diagram verification analysis, as shown in Figure 8.

It can be seen from the above diagram that the actual vertical levitation magnetic force is basically consistent with the attenuation trend of the simulation curve, and the actual bearing capacity is above 80% of the theoretical bearing capacity. The actual vehicle bearing capacity is affected not only by suspension clearance and horizontal offset, but also by external factors such as permanent magnet magnetization state, magnetic conductors and magnetic flux leakage. In addition, in the design of the "Rainbow" suspension guidance system, there is a certain offset redundancy and the nonlinear variation of the horizontal and vertical force in the steering mechanical structure, which often leads to the instability of the actual suspension position. As a result, part of the position was mismeasured is also possible. Combined with the whole sample data, the finite element simulation capacity is basically consistent with the actual suspension bearing capacity, which provides a certain scientific research value for the subsequent suspension stability control.

In the mixed suspension structure, the static suspension mainly depends on the permanent magnet, which needs a large number of permanent magnets laid along both sides of the track in the engineering construction. However, the precious rare earth resources lead to the high price of the high-performance permanent magnet in the market. This will also affect the application of the "Rainbow" system. As far as construction cost is concerned, compared with the traditional rail transit system, the system has the advantage of lower cost,



（a） （b）

FIGURE 9. Halbach permanent magnet array gridding and the effect of laminated plate thickness on vertical magnetic force.

but in engineering and design, it should save materials and reduce engineering cost as much as possible while ensuring the basic requirements of vehicles. Therefore, the combination of Halbach permanent magnet array is simulated in this paper.

From the simulation results of levitation force and horizontal force, it can be seen that the static magnetic field force between permanent magnets is large, which is very difficult for engineering assembly and can easily cause bumps between permanent magnets. For this purpose, non-magnetic materials (such as epoxy resin) were filled in the Halbach permanent magnet array combination gap. In this way, not only the difficulty of permanent magnet assembly can be effectively reduced, but also the demand for permanent magnets in practical construction can be reduced to a certain extent. It can be seen from the simulation that the thickness of the laminated plate has a certain influence on the levitation magnetic force, and the influence degree of the thickness is shown in Figure 9.

Figure (a), we pay attention to the skin effect between permanent magnets, the simulation surface depth is set to 2 mm; In figure (b), x1 denotes the thickness of the adding layer, x denotes the displacement of the short rail along the direction of the track, and the starting point of the short rail is set to (150 + X) mm, the thickness of adding layer is set to (5 + X) mm; the starting point of the long rail is set to 0 mm, the thickness of the adding layer is [0,5] and the sampling step is 1 mm.

It can be seen from the above figure that the thickness of the laminated plate has obvious influence on the maximum vertical levitation magnetic force. The five groups of data all have a certain degree of magnetic attenuation, and the attenuation rate of the adjacent thickness curve is about 0.5%. Because the magnetic field distribution is relatively uniform and the magnetic force is large, the effect of laminated plate on the stability of the whole suspension force is relatively small, so the curve is basically kept smooth. To sum up, the thickness of the laminated plate should be considered synthetically in the actual engineering design, such as the actual load requirement and the cost estimate and so on.

D. STABILITY ANALYSIS OF SUSPENSION SYSTEM

In the electromaglev system composed of Halbach permanent magnet array, due to the lack of damping term in the equation of state of the system, the system presents a critical stable state [15]; At the same time, the static suspension system also presents a certain volatility in the actual suspension magnetic force detection, so this paper will combine the magnetic force analysis of the suspension system to judge the stability of the static suspension system.

Since the 1970s, researchers have put forward many strategies for the study of magnetic field of Halbach permanent magnetic arrays, which can be divided into: finite element simulation [16], sinusoidal approximation [17], electronic circulation analysis [18], magnetic charge method [19]. However, in many research methods, magnetic field analysis is often carried out for the modes of rotating motor [20] and electric suspension structure [21], but there are few references for static magnetic force analysis between double-layer Halbach permanent magnetic arrays. Therefore, in this paper, the finite element magnetic simulation curve is obtained by MATLAB fitting tool between vertical levitation force and suspension clearance. According to the fitting function, the steady state analysis of the static suspension system is carried out.

The fitting function is as follows: the confidence interval is 95%.

$$F\left(h\right)=a*e^{\left(b*h\right)}+c \tag{1}$$

The magnetic force function of the levitation height **h** is the **F(h)**, and the fitting parameter is:

$$a=3426,\quad b=-58.26,\quad c=202.2$$

Functional fitness:

$$\begin{cases} SSE=0.0116 \\ R-square=0.9996>0.9 \\ RMSE=0.01747 \end{cases} \tag{2}$$

According to formula (2), the fitting function is in excellent agreement with the actual levitation magnetic force.

According to Newton's second law and equation of suspension (1), the equation of state of levitation system in vertical magnetic field can be obtained, without considering the influence of horizontal deviation.

$$\begin{cases} \dot{h} = v \\ \dot{v} = F\left(h\right)/m - g \end{cases} \tag{3}$$

In the formula, **v** denotes the displacement velocity of the vehicle in the vertical direction and **m** represents the mass of the whole suspension structure.

For this kind of time-varying suspension systems, researchers often study the stability of the controlled system by analyzing the stability of the system at the equilibrium point. In reference [22], it is shown that there is a nonlinear exponential function relationship between the magnetic field of single layer Halbach and the suspension gap. In the actual suspension control, the adjustable control range of the general electromagnetic maglev train is kept within the 3mm, while the "Rainbow" suspension system is designed to develop the "personal rapid rail transit system", that is, the carrying capacity of the car can contain 4-6 people. Combined with the simulation curve of suspension force, the height of suspension control is basically kept within the adjustable range of 5 mm, in addition, on the suspension frame mechanical protective wheels with horizontal and vertical direction are set to avoid large suspension fluctuation of suspension structure. Therefore, by obtaining the equilibrium point, the stability of the equation of state of the system is analyzed by using the Taylor formula in the local linearization expansion at the equilibrium point.

At the equilibrium point, the equation of suspended state is:

$$\begin{cases} \dot{h} = v = 0 \\ \dot{v} = \dfrac{a * e^{(b*h)} + c}{m} - g = 0 \end{cases} \tag{4}$$

By formula (4), we can get:

$$\begin{cases} v_0 = 0 \\ h_0 = \dfrac{1}{b} * ln(\dfrac{mg - c}{a}) \end{cases} \tag{5}$$

In the formula (5), the parameters can be calculated or measured in practice, that is, when the mass of the vehicle is known, the suspension height under the static magnetic field will be stabilized at h_0 and the vertical displacement velocity will be zero.

When formula (3) is expanded by Taylor formula, the linearized equation of state is obtained as follows:

$$\begin{cases} \dot{h} = v \\ \dot{v} = \mathrm{k}(h - h_0) \end{cases} \tag{6}$$

Among them, $\mathrm{k} = \frac{b(mg-c)}{m}$, assume that $\mathrm{x} = h - h_0$, $\mathrm{y} = v$. The equation of state space of the system can be obtained:

$$\begin{bmatrix} \dot{\mathrm{x}} \\ \dot{\mathrm{y}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \mathrm{k} & 0 \end{bmatrix} \begin{bmatrix} \mathrm{x} \\ \mathrm{y} \end{bmatrix} \tag{7}$$

From the formula (7), the characteristic equation of the suspension system is obtained as follows: $\lambda^2 + k = 0$.

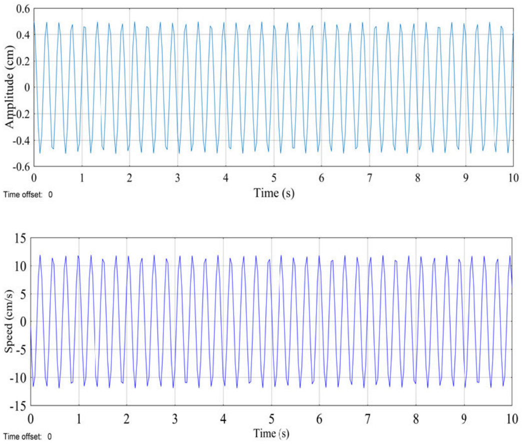


FIGURE 10. **Response waveform of vertical displacement and velocity.**

From (1) we know that $b < 0$, $mg \gg c$. Therefore, the state matrix equation of the system is the second order system, and its eigenvalue has a pair of imaginary real roots with the real part as zero, that is, the system is in the state of zero damping [23] (pp. 51–63), $\lambda 1, 2 = \pm \mathrm{j}\sqrt{k}$. In other words, the equilibrium point of the suspension system under the static magnetic field is critical stable after linearization.

Combined with the above deduction, the formula (7) is solved numerically at a certain equilibrium point by using MATLAB simulation platform. Taking $m = 750kg$, $g = 10m/s^2$, initial value $(h_0, v_0) = (28, -1)$, 23mm is the height of suspension in response to the equilibrium point, and the dynamic trend of suspension frame under the action of static magnetic field can be obtained, as shown in Figure 10. From the velocity curve and displacement curve, it can be seen that a single static permanent magnet structure can realize the relative stability of the suspension system, but the response of the system will be close to the equal-amplitude oscillation when there is a slight external disturbance. Moreover, it is not controllable by itself.

E. DESIGN AND ANALYSIS OF ELECTROMAGNETIC CONSTRAINED DAMPING SYSTEM

In the analysis of the above section, the train suspension system cannot meet the requirements of train safety and stability only by static magnetic force. Combined with the development of modern electromagnetic permanent magnet hybrid magnetic levitation technology, electromagnetic constrained damping system is introduced into the "Rainbow" suspension system, and the static magnetic field force is supplemented and slowed down by using the controllability of electromagnetic force. The hybrid suspension structure can be divided into permanent magnet array and electromagnetic coil, and its structure is three views, as shown in Figure 11.

F. PHYSICAL MODELS

First, it is assumed that there is no magnetic field coupling between the electromagnetic winding and the Halbach

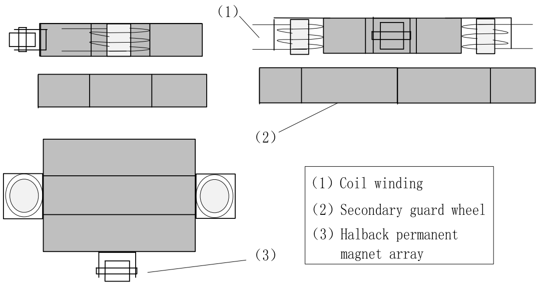


FIGURE 11. Three views of hybrid suspension structure.

permanent magnet array, and the electromagnet is in the state of non-magnetic saturation and so on. In ideal conditions, the suspension is subjected only to magnetic field force and vehicle gravity, in the vertical direction of the dynamic equation:

$$\begin{cases} m\dfrac{d^2h(t)}{dt^2} = F_0 + mg \\ F_0 = F_1(i,h) + F_2(h) \end{cases} \tag{8}$$

In the formula: $\boldsymbol{F_0}$ -- magnetic field force, $\boldsymbol{F_1(i,h)}$-- Electromagnetic force, $\boldsymbol{F_2(h)}$-- magnetic field force of permanent magnet, $\boldsymbol{g}$ --gravity acceleration, The equation of electromagnetic force for single point electromagnetic system [24]:

$$\begin{cases} F_1(i,h) = K\left(\dfrac{i}{h}\right)^2 \\ K = -\dfrac{u_0SN^2}{4} \end{cases} \tag{9}$$

The relationship between voltage and current in the electromagnet winding can be expressed as follows:

$$U(t) = Ri(t) + l_1\frac{di(t)}{dt} \tag{10}$$

In the formula: **R--** electromagnet winding resistance, $\boldsymbol{l_1}$ -- equivalent inductance of electromagnet winding.

When the suspension system is in the equilibrium position, the suspension system under the static magnetic field realizes the critical stable state, and the electromagnetic constrained damping system achieves the effect of fine tuning the suspension state, then the real-time control of the hybrid system belongs to a kind of bounded regulation. From the expressions (1) and (9), we can see that the magnetic force of the suspension system has a complex nonlinear relationship. Therefore, in this paper, the nonlinear system is linearized by Taylor series at the suspension equilibrium.

Suppose that (i_0, h_0) is an equilibrium point of a hybrid suspension system, which is obtained by (8):

$$0 = F_1(i_0,h_0) + F_2(h_0) + mg \tag{11}$$

It is easy to obtain the Taylor formula expansion (neglecting the higher-order term) for the magnetic force of (8):

$$\begin{cases} F_0 = F(i,h) = F_1(i_0,h_0) + F_2(h_0) \\ \qquad + F_1'(i_0,h_0) + F_2'(h_0) \\ F_1'(i_0,h_0) = f_i'(i_0,h_0)(i-i_0) \\ \qquad + f_h'(i_0,h_0)(h-h_0) \\ F_2'(h_0) = f_h'(h_0)(h-h_0) \end{cases} \tag{12}$$

$\mathrm{F}_i(i_0,h_0)$, $\mathrm{F}_h(i_0,h_0)$ is derived from the differential partial derivative formula:

$$\begin{cases} f_i(i_0,h_0) = \left(\dfrac{\partial f_1(i,h)}{\partial i} \mid i=i_0, h=h_0\right) \\ \qquad = 2K\dfrac{i_0}{h_0^2} \\ f_h(i_0,h_0) = \left(\dfrac{\partial f_1(i,h)}{\partial h} \mid i=i_0, h=h_0\right) \\ \qquad = -2K\dfrac{i_0^2}{h_0^3} \\ F_2'(h_0) = \left(\dfrac{\partial f_2(h)}{\partial h} \mid i=i_0, h=h_0\right) \\ \qquad = abe^{bh_0} \end{cases} \tag{13}$$

To simplify the expression, it is assumed that k_{1h}, k_{1i}, k_2 represents the first partial derivative of the electromagnetic force to the gap and current at the equilibrium point, and the first partial derivative of the static magnetic field force to the gap, respectively. Available from the formula (12) and (13):

$$\begin{aligned} F(i,h) &= (F_1(i_0,h_0) + F_2(h_0)) \\ &\quad + (k_{1i}(i-i_0) + k_{1h}(h-h_0) + k_2(h-h_0)) \end{aligned} \tag{14}$$

The system model equation after linearization can be obtained by substituting the formula (11) with the formula (14):

$$m\frac{d^2h(t)}{dt^2} = k_{1i}(i-i_0) + (k_{1h}+k_2)(h-h_0) \tag{15}$$

Laplace transformation for linearized model equation:

$$\frac{h(s)}{I(s)} = \frac{k_{1i}}{ms^2 - (k_{1h}+k_2)} \tag{16}$$

The controlled output relationship between gap and current is described in formula (16), and the controlled relation between voltage and gap can be transformed by formula (10).

In addition, the characteristic equations of electromagnetic permanent magnet hybrid open loop suspension system can be obtained by (16).

$$ms^2 - (k_{1h}+k_2) + k_{1i} = 0 \tag{17}$$

Due to k < 0, the open-loop poles of levitation system are easily obtained:

$$s_{1,2} = \pm\sqrt{\frac{1}{m}\left[\left(abe^{bh_0} - 2K\frac{i_0^2}{h_0^3}\right) - 2K\frac{i_0}{h_0^2}\right]} \tag{18}$$

There is an open loop pole in the right half plane on the complex plane of the system. According to the Routh Criterion, the hybrid suspension structure composed of permanent magnet array and electromagnetic constrained damping system belongs to an unstable structure of its own, but the system is still observable and controllable. The suspension control model can be adjusted by external control strategy to make the whole suspension system stable.

G. ELECTROMAGLEV CONTROL STRATEGY

Because the oscillation amplitude of the hybrid suspension control system is relatively small under the stable state, the suspension force under the static magnetic field can be approximately considered as a constant value, while the electromagnetic constrained damping system can suppress and adjust the momentum of the suspension oscillation.

Combined with the formulas (8) and (11), it is obtained that:

$$\mathrm{m}\frac{d^2h(t)}{dt^2} = F_2(h_0) + mg + K\left(\frac{i}{h}\right)^2 \tag{19}$$

The state space equation of the electromaglev control system is obtained by expanding at the equilibrium point:

$$\begin{cases} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{k_{1h}}{m} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{k_{1i}}{m} \end{bmatrix} I \\ y = [1\ \ 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{cases} \tag{20}$$

In the formula, x 1 and x 2 represent suspension displacement and suspension displacement velocity, respectively. Clearly, in the matrix rank discriminant of the equation of state:

$$\begin{cases} w_c = [B\ \ AB\,] = \begin{bmatrix} 0 & \frac{k_{1i}}{m} \\ \frac{k_{1i}}{m} & 0 \end{bmatrix} \neq 0 \\ M_c = [C\ \ CA\,]^T = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \neq 0 \end{cases} \tag{21}$$

The system has complete controllability and observability.

H. EXPERIMENTAL VERIFICATION AND DISCUSSIONS

At present, the project is still in the basic research stage, and the electromagnetic constrained damping system is still in the theoretical stage, but its structure and principle are basically the same as the electromagnetic suspension ball system. In this paper, the control strategy of electromagnetic constrained damping in a single point suspension ball system is studied.

The state space model of the suspension system based on the parameters of the real single point suspension ball system is as follows:

$$\begin{cases} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 980 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 2499 \end{bmatrix} U \\ y = [1\ \ 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \end{cases} \tag{22}$$

In the formula, x1 and x2 represent the displacement and velocity of the suspension ball respectively, and the matrix rank discriminant $w_c > 0, M_c > 0$, respectively.

For linearized systems, the state feedback control of linear time-invariant systems can be used for pole assignment of formula (22). According to the expected performance of actual control, this paper selects the dynamic control performance index: the overshoot quantity $\delta_1 \leq 5\%$, and the adjustment time is less than 3 s. Combined with the reference [25] (p.111), the performance index of the controlled object is deduced, and the damping ratio $\xi \geq 0.69$ and the natural frequency $\omega_n \geq 1.65$ are obtained under the preset state.

The corresponding expected closed-loop dominant poles (critical points) are:

$$\begin{aligned} s_{1,2} &= -\xi\omega_n \pm \omega_n\sqrt{\xi^2 - 1} \\ &= -1.138 \pm j1.194 \end{aligned} \tag{23}$$

The characteristic polynomials of the state feedback system are as follows:

$$\begin{aligned} |\lambda\mathrm{I} - (\mathrm{A} - \mathrm{bK})| &= (s + 1.138 + j1.194)(s + 1.138 + j1.194) \\ &= s^2 + 2.276s + 2.721 \end{aligned} \tag{24}$$

If the corresponding coefficient is equal, the feedback matrix is obtained:

$$\overline{\mathrm{K}} = [1516.279 \quad -2.276]$$

$$\begin{cases} P_1 = [B\ \ AB\,] \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 2499 & 0 \\ 0 & 2499 \end{bmatrix} \\ K = \overline{\mathrm{K}}P_1^{-1} = \begin{bmatrix} \frac{1516.279}{2499} & \frac{-2.276}{2499} \end{bmatrix} \end{cases} \tag{25}$$

The linearized state space equation after the state feedback pole assignment method is as follows:

$$\begin{aligned} \begin{bmatrix} \dot{x_1} \\ \dot{x_2} \end{bmatrix} &= [A + BK] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \mathrm{B}U \\ &= \begin{bmatrix} 0 & 1 \\ 2496.279 & -2.726 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 2499 \end{bmatrix} U \end{aligned} \tag{26}$$

The state feedback control strategy is tested on a single point suspension ball system, as shown in figure 12-14.

According to the above theoretical derivation, the system model with linearized pole assignment is simulated in MATLAB/Simulink. Among them, the output voltage is set to 5.8 V, the suspension ball position is basically stable at 5.1mm (distance to the bottom of the winding coil), and the adjusting time is about 2 s, as shown in Figure 12 below.

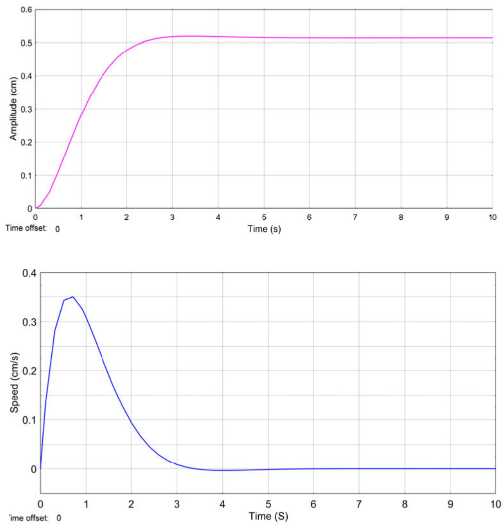


FIGURE 12. Output curve of suspension system under linear state control.

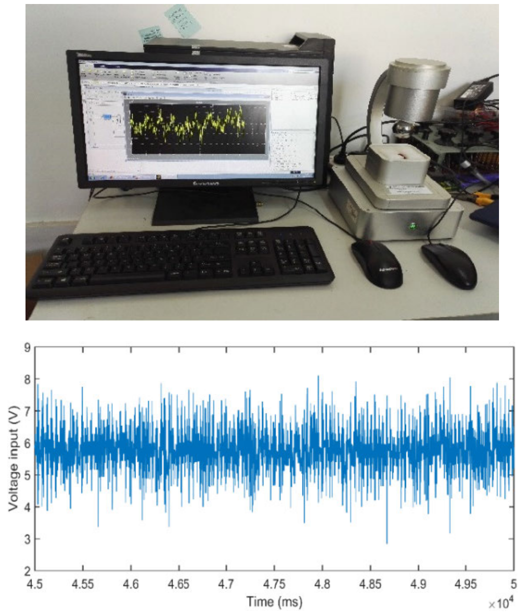


FIGURE 13. Output response of suspension ball system.

I. EXPERIMENTAL RESULT

A single point suspension ball system belongs to a voltage input electromagnetic adsorption suspension structure. In the actual control system, the voltage input signal of the suspension system is analyzed. In Figure 13 and 14, the initial voltage signal is set to 5.8 V and the system responds to the voltage curve within 5 S. From the system response, it can be seen that the signal input is basically stable at 5.8V, and remains within the fluctuation range of [5.5,6.5]. Among them, there is obvious ''instantaneous burr pulse'' phenomenon in the unit time voltage output. From the point of view of control algorithm, linear state feedback control belongs to a real-time dynamic adjustment strategy. The voltage output of the floating system is adjusted in real time by the change of the position of the suspension ball. In terms of the hardware structure of the suspension system, the type of circuit components used in the system (including capacitance, resistive device, digital-to-analog converter, etc.) will also affect the quality of the system response output. Therefore, there are a few burr pulses in the voltage response of the system, which can be regarded as the signal output within a reasonable range.

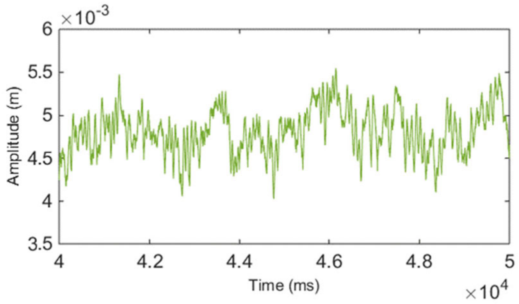


FIGURE 14. Actual suspension ball position control curve.

In the suspension structure of the ''Rainbow'' system, the stable oscillation of permanent magnet static magnetic field maintains in 5 mm, the ultimate purpose of electromagnetic structure design is to use electromagnetic restraint damper to suppress vibration impulse in real time, to slow down vehicle oscillation, and to ensure the safety and comfort of train operation. For a single point suspension ball system, the linearized state feedback control has a good control effect. The suspension ball is basically stable within the 2 mm range, that is, the vibration range is 4 to 6 mm, and it has a strong ability to adjust the disturbance. Therefore, the linear state feedback control strategy is feasible and reasonable.

IV. CONCLUSION AND FUTURE WORK

For small and medium-sized cities, the increasing demand for urban transportation, the serious lag in the construction of subway and other rail transit, and the acceleration of the pace of urban life, the demand for the construction of a new type of urban rail transit system is increasingly urgent. On the other hand, with the development of maglev technology and the gradual completion of commercialization process of maglev train, The advantages of energy-saving and environmental protection and strong adaptability of medium and low speed maglev trains have become increasingly prominent and the potential commercialization advantages have gradually emerged, making it the research hotspots for the next generation development of urban rail transit technology. Therefore, For the diversification of urban rail transit system, the quality of public facilities in the future and the trend of individualized development, in this paper, a new intelligent permanent magnet maglev rail transit system is proposed. The system consists of Halbach permanent magnet array suspension control system, permanent magnet linear synchronous motor drive system, intelligent communication system and operation control system. Each part realizes stable operation through intelligent coordination of central control unit. The system has the advantages of intelligence, ecology, economy and so on. It is suitable for the development of public transportation and urban landscape construction in modern and future small and medium-sized cities. Finally, the feasibility of the suspension control system is simulated and analyzed by Finite Element Method using Maxwell software. The stability of the suspension structure of the train is demonstrated by the electromagnetic suspension control system. The results show that the electromagnetic permanent magnet hybrid suspension structure is reasonable and security.

The proposing of the ‘‘Rainbow’’ system is aimed at the development of a new traffic system with small-sized maglev trains at medium and low speed in the future, it is one of the effective ways to realize the zero emission of urban public facilities and alleviate the criticism of urban public transport system. It is also an important reference for the development of new PRT traffic system in the future, and opens a new way for the development and application of maglev technology. Combined with the latest developments of maglev trains in China, a rail transit network system with 'high speed maglev train connecting node cities, medium and low speed maglev as urban artery and small magnetic levitation as terminal access' may be formed in the future. Together with roads, railways, airplanes, shipping and pipeline transportation, they will form an integrated modern transportation system.

At present, the ‘‘Rainbow’’ system is still in the stage of theoretical research and infrastructure experiment, and there is still the need for the optimization and improvement of the structure and operation control system. The next work will be carried out in the following aspects: (1) extension of the test line: the first phase of the engineering test line is only 60 meters, supported by the station room and four columns, used for basic theoretical research and feasibility verification. Next, the test line will be extended to 336 meters, by which time the extended line will cover all experimental operating environments such as straight lines, bends, steep slopes, track switches, as well as vehicle marshalling operations. (2) structural optimization, cost reduction: in static suspension structures, horizontal steering force is subjected to horizontal deviation. How to optimize the permanent magnet structure to reduce the difficulty of steering system control will be one of the next research directions. (3) Electromagnetically constrained damper and electromagnetic guiding structure: in the suspension and guiding system, the electromagnetic winding module is introduced, the electromagnetic winding is used to increase the damping, and the vertical vibration of the system is suppressed; The mechanical guide wheel is replaced by electromagnetic guide to achieve the non-contact guidance of system and the non-contact operation. (4) track switch: the existing maglev technology is still weak in the switch control system. Its efficiency and reliability need to be improved. The research team further explored new types of track switches of electromagnetic structures and suspension guides, including simple turnout, double slip switches etc., to achieve a more concise and efficient switch system is one of the key technologies to be solved in the development of maglev technology in the future. (5) Application and promotion: in view of the strong climbing ability, small turning radius and light weight of the system, instead of occupying land, the ‘‘Rainbow’’ system will actively seek to promote and apply the complex environment, such as bay, valley, channel, cross-river and so on, as well as the special town, campus and so on, to provide a reference and reference for modern intelligent traffic.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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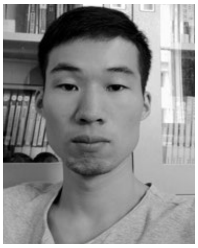

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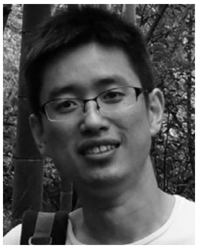

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