Model Establishment and Simulation Analysis of Permanent Maglev Vehicle

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***Abstract*—Based on the principle of variable magnetic flux, a permanent magnet suspension vehicle is proposed in this paper. The device adopts a four-point suspension structure and provides driving force through a permanent magnet gear. By changing the rotation angle of the disk permanent magnet of the four magnetic poles, the magnetic flux is changed. It could achieve the suspension force equal to gravity, so that the stable suspension of the device is realized. According to the suspension force model and the structure of prototype, a control decoupling system model is established. The decoupling strategy changes the four-point independent control into the control suspension vehicle with three degrees of freedom. The simulation results show that the decoupling control method is effective and worthy of further verification through experiments.**

I. INTRDUCTION

With the improvement of manufacturing technology, the requirements of precision parts and electronic components for cleaner production environment are more stringent. However, traditional equipment is difficult to meet the requirement. Magnetic levitation technology has no contact and no coulomb friction. It can effectively avoid the secondary dust and ensure the cleanliness of the environment. In recent years, with the development of research on rare earth permanent magnetic materials, the magnetic energy characteristics of permanent magnet materials have been greatly improved, and the application of permanent magnetic levitation technology has been further expanded. Permanent magnetic levitation technology has been applied to maglev bearings, maglev platforms, maglev trains and maglev transport devices [1-4].

The principle of permanent magnetic levitation is to achieve stable levitation by controlling the magnitude of magnetic force equal to the gravity of the suspended target. In the magnetic suspension systems using permanent magnets, there are mainly two control methods of suspension forces, which are the air gap length control and the variable flux path control. The first method controls the suspension force by adjusting the length of the air gap between the permanent magnet and the suspended object. Another one is the variable magnetic circuit control method, which sets up a magnetic resistance adjustment mechanism in the magnetic flux loop to control the levitation force [5]. However, most magnetic suspension systems have a critical problem, which is once the suspended object adheres to the permanent magnets or the magnetic yokes, the suspended object cannot be controlled any more, unless another force is used to detach the suspended object from the magnets or magnetic yokes.

However, neither of these two methods can realize zero levitation force, and the contact adsorption problem is one of the shortcomings of the existing permanent magnetic levitation system. F. SUN has proposed a variable magnetic circuit permanent maglev system, which can realize zero levitation force [6]. In this suspension system, the suspension force is controlled by a variable magnetic flux path mechanism where the flux path is changed by varying the angle of the magnet. This system can generate a semi-zero suspension force, which can overcome the fore-mentioned disadvantage of the magnetic suspension system using permanent magnets. Based on this system, a permanent magnetic levitation dustless transport vehicle is designed in this paper. The suspension part adopts a four-point suspension platform structure, which is totally dependent on permanent magnets for levitation.

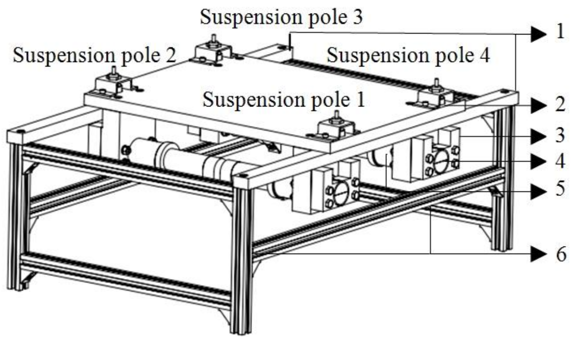
Solving the problem of control coupling is the focus of many scholars who research four-point suspension platform. M. Q. Jing proposed a two-dimensional high-precision magnetic levitation positioning platform, which uses four pairs of differential electromagnets to realize magnetic levitation support, and independently controls the stable suspension through a four-channel PID controller. This control mode exists the coupling between each channel [7]. L. C. Li adopted coordinate transformation to eliminate the control coupling problem in maglev platform system [8]. B. I. Annasiwaththa established the mathematical model for the MagLevLS (Magnetically Levitated Linear Slider) platform with this method [9].According to the state feedback method and coordinate transformation method, Q. H. Chen designed the controller applied to the magnetic suspension platform respectively. The simulation results showed that the second method had better response characteristics [10].

In this paper, the mathematical model of the permanent maglev vehicle was established by using coordinate transformation method, and the three-channel independent controller was designed. Finally, the decoupling model and control method were verified by simulation. The purpose of this paper is to explore the whether the decoupling control is an effective method of solving control coupling of the suspension platform.

II. STRUCTURE AND PRINCIPLE

A. Experimental prototype

The prototype model of the permanent magnet suspension vehicle is shown in Figure 1 (where the drive device is not shown). The prototype mainly consists of suspension platform, suspension guide rail and aluminum profile frame. Four levitation poles are installed under the suspension platform. Each pole consists mainly of a disk PM(permanent magnet), a rotary actuator containing a harmonic reducer and an encoder, a pair of opposite F-type permalloy iron yoke and a eddy current sensor. The permalloy yoke around disk PM are partially designed to be circular in shape to reduce magnetic leakage in the magnetic circuit. The suspension platform is in contact with the rail when it is not floating. The experimental prototype is installed on the worktable to avoid the adverse effects of vibration on the suspension experiment.



1-Suspension guide rail 2-Eddy current sensor 3-Permalloy iron yoke 4-Disk permanent magnet 5-Rotary actuator(A motor with reducer and encoder) 6-Aluminum profile frame.

Figure 1. Prototype model of permanent Maglev vehicle

According to drawings, we have finished tasks of components manufacture and assemblage. The experimental device is shown in Figure 2. The length of suspension guide rail is 600mm and the material of rail is steel. The size of suspension platform is 300mm × 400mm. Its material is polyoxy-methylene, characterized by light weight, but high mechanical strength, high rigidity and high hardness. The eddy current sensor is TR81, of which the linear range is from 1mm to 6mm and the nonlinear error is 1.5%. For disk PM which is magnetized along the radial direction, the diameter is 30 mm and the thickness is 20mm. The rated speed of the motor is 8040 rpm, which ensures the system has the ability of quick response. The motor is combined with harmonic reducer and photoelectric encoder, the deceleration ratio of reducer is 50, and the encoder rotates one cycle to output 500 pulse signals.

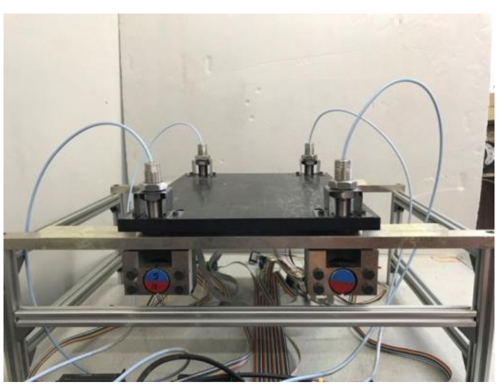
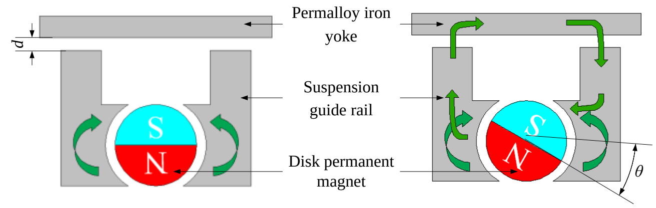


Figure 2. Experimental prototype of permanent maglev vehicle

B. *Suspension principle*

The suspension of platform is realized by changing the effective magnetic flux in the guide rail. That is, the servo motor directly drives the disk permanent magnet to rotate, changes the corresponding rotation angle to realize the change of effective magnetic flux, and then controls the levitation force. Detailed structure and principle are shown in Figure 3.



a) Rotation angle is 0   b) Rotation angle is θ

Figure 3. Suspension principle of single suspension pole e

The state shown in Figure 3a) is an initial position, where the permanent magnet rotates at an angle of 0 º. In this state, N pole is on the top and S pole is just below it, which means all of the magnetic induction lines from the N pole passing through two iron yoke instead of the guide rail to the S pole. Thus, there is no suspension force between the rail and the iron yoke. As shown in Figure 3b), the permanent magnet rotates at θ angle. Meanwhile, part of the magnetic inductance lines pass through the right iron yoke from the N pole, through the guide rail, and return to the S pole through the left iron yoke. Therefore, there is a suspension force generating between the guide rail and the iron yoke. With the increasing rotation angle of the disk PM, the number of magnetic induction line passing through the guide rail is growing. As a result, the suspension force is increased gradually. It indicates that the levitation force between the two iron yokes and the guide rail can be controlled by changing the rotation angle of the disk PM.

III. DYNAMIC MODEL

A. *Coordinate transformation*

In the absolute coordinate system O, analysis of the suspended platform in Figure 4 show that the system has three degrees of freedom: z represents the displacement of the center of mass in the Z direction, and α and β is the rotation angle of the platform around the axis of X and Y respectively. The direction of counterclockwise rotation is positive. In the stable suspension position, the three degrees of freedom of the platform have a coordinate transformation relationship with the translational degrees of freedom of each magnetic pole: z_1, z_2, z_3, z_4. According to the disturbance of three degrees of freedom, the displacement of the magnetic poles along the Z axis can be obtained. Next, the process of coordinate transformation will be introduced through analysis and derivation in detail.

The suspended platform is regarded as a rigid body. When the platform rotates angle of α or β respectively at a micro-displacement, the suspension gap of each magnetic pole will be changed, as shown in the Figure 5. The distance between center of Pole 1 and Pole 2 is $2e$, and the distance between pole 1 and pole 3 is $2b$. Take the pole 1 as an example:

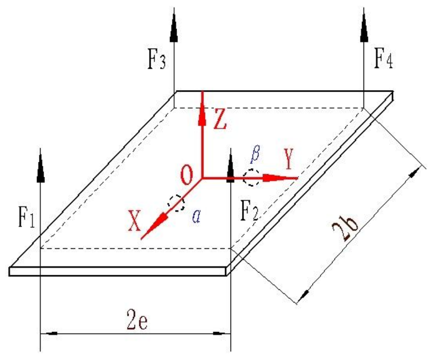
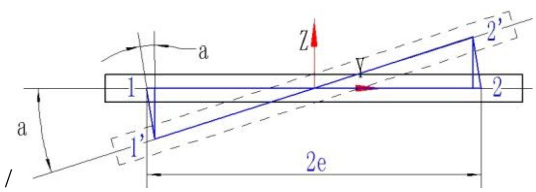
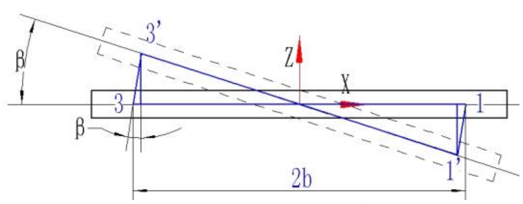


Figure 4. The force diagram of suspension platform

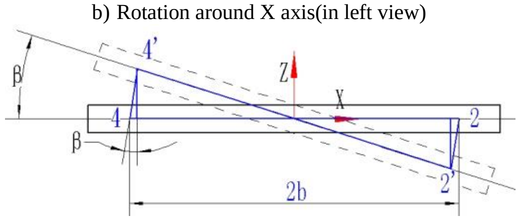
At the equilibrium position, z is the micro-displacement of the coordinate origin O, and its direction is the same as that of z_1.



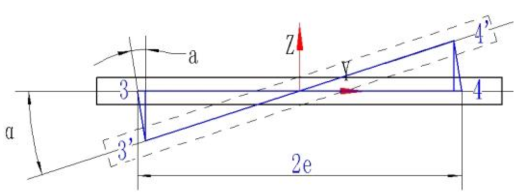
a) Rotation around X axis(in front view)



b) Rotation around X axis(in left view)



c) Rotation around X axis(in right view)



d) Rotation around Y axis(in back view)

Figure 5. The schematic diagram of coordinate transformation principle

The small angle α disturbance produces a downward displacement in the z_1 direction.

$$\Delta z_{1\alpha} = -e \bullet \sin\alpha \approx -e \bullet \alpha \tag{1}$$

The small angle β disturbance also produces a downward displacement in the z_1 direction.

$$\Delta z_{1\beta} = -b \bullet \sin\beta \approx -b \bullet \beta \tag{2}$$

So the coordinate transformation formula of z_1 direction is

$$z_1 = z - e\alpha - b\beta \tag{3}$$

The formula of other magnetic poles can be obtained by the same principle. It can be expressed as a matrix:

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} 1 & -e & -b \\ 1 & e & -b \\ 1 & -e & b \\ 1 & e & b \end{bmatrix} \begin{bmatrix} z \\ \alpha \\ \beta \end{bmatrix} \tag{4}$$

Where, the relationship between the three degree freedom of the platform and the displacement of the four magnetic poles can be expressed by matrix. And $\mathbf{N}_1$ is called coordinate transformation matrix. $\mathbf{N_2}$ is called coordinate inverse transformation matrix. Obviously, the two matrixes satisfy the relationship showed in equation (7).

$$\mathbf{N_2} = \begin{bmatrix} 1 & -e & -b \\ 1 & e & -b \\ 1 & -e & b \\ 1 & e & b \end{bmatrix} \tag{5}$$

$$\mathbf{N}_1 = \frac{1}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -\frac{1}{e} & \frac{1}{e} & -\frac{1}{e} & \frac{1}{e} \\ -\frac{1}{b} & -\frac{1}{b} & \frac{1}{b} & \frac{1}{b} \end{bmatrix} \tag{6}$$

$$\mathbf{N}_1 \mathbf{N}_2 = \mathbf{E}_{3\times3} \tag{7}$$

B. Single pole mechanics model

According to the existing research results, we established the mathematical model of suspension force and torque.

$$F_n = k_m \frac{\sin^2\theta_n}{(d_n + \Delta d_f)^2} \tag{8}$$

Where k_m is a proportionality coefficient of attractive force and Δd_f is a compensation coefficient of air gap. The parameter n represents different magnetic poles, $n=1, 2, 3, 4$.

$$T_n = k_\tau \frac{\sin 2\theta_n}{(d_n + \Delta d_\tau)} \tag{9}$$

Where k_τ is a proportionality coefficient of rotational torque and Δd_τ is a compensation coefficient of air gap.

The model was verified by ANSYS software. And the distance between the guide rail and the permalloy iron yoke varied from 1mm to 5mm, with an interval of 1 mm. With the magnet rotating 360°, the suspension force of the rail and the torque of the magnet are shown in Figure 6 and Figure 7. It can be seen that the relationship between the levitation force and the angle of the magnet is in accordance with the model established before. The suspension force is very nonlinear, which makes it difficult to control.

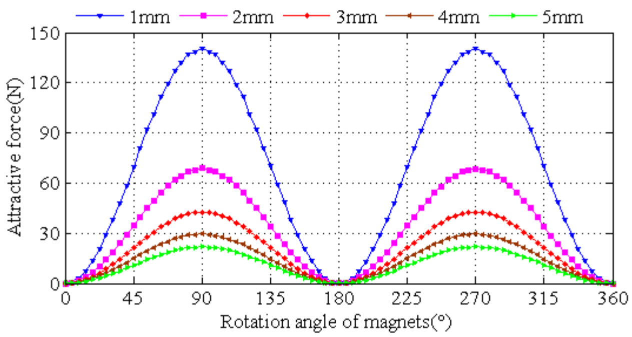


Figure 6. The simulation result of suspension force

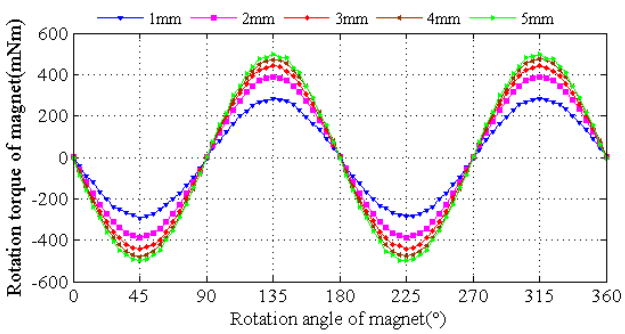


Figure 7. The simulation result of torque

The complex model is linearized at the equilibrium position (d_0, θ_0).

$$F_n = F(d_0,\theta_0) + k_d z_n + k_\theta \Delta\theta_n \tag{10}$$

$$T_n = T(d_0,\theta_0) + k_a z_n + k_b \Delta\theta_n \tag{11}$$

Where,

$$z_n = -\ d - d_0\ ,\ \Delta\theta_n = \theta - \theta_0$$

$$k_d = -\frac{2k_m \sin^2\theta_0}{(d_0+\Delta d_f)^3},\ \ k_\theta = \frac{k_m \sin 2\theta_0}{(d_0+\Delta d_f)^2}$$

$$k_a = -\frac{k_\tau \sin 2\theta_0}{(d_n+\Delta d_\tau)^2},\ \ k_b = \frac{2k_\tau \cos 2\theta_0}{(d_n+\Delta d_\tau)}$$

C. Mathematical model

According to the previous analysis, the suspension platform has three degrees of freedom. Therefore, the system dynamics model was established by using of lagrange equations.

$$\begin{cases} m\ddot{z} = c_1\dot{z} + F_1 + F_2 + F_3 + F_4 - mg \\ J_\alpha \ddot{\alpha} = c_2\dot{\alpha} + (-F_1 + F_2 - F_3 + F_4)e \\ J_\beta \ddot{\beta} = c_3\dot{\beta} + (-F_1 - F_2 + F_3 + F_4)b \end{cases} \tag{12}$$

Based on the suspension force model and simplified by coordinate transformation, the equation can be obtained.

$$\begin{cases} m\ddot{z} = -c_1\dot{z} + 4k_d z + 4k_\theta\theta_z \\ J_\alpha \ddot{\alpha} = -c_2\dot{\alpha} + 4k_d e^2\alpha + k_\theta e^2\theta_\alpha \\ J_\beta \ddot{\beta} = -c_3\dot{\beta} + 4k_d b^2\beta + k_\theta b^2\theta_\beta \end{cases} \tag{13}$$

Where, θ_z, θ_α and θ_β are inversely transformed with the rotation angle of magnets at each pole.

$$\begin{bmatrix} \theta_z \\ \theta_\alpha \\ \theta_\beta \end{bmatrix} = \mathbf{N}_1 \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix}$$

The rotation angle of the magnet is controlled by the motor with the input current, and the current-angle conversion model of each pole is established in equation(14). The effect of air gap change on torque of magnets is very small, so the influence of air gap variation on torque can be ignored.

$$J\ddot{\theta}_n = k_i \Delta i_n + k_b \theta_n + c_4 \dot{\theta}_n \tag{14}$$

The equation(13) and equation(14) can represent the complete model of the system. In this section, the decoupling model of the system is established by the way of coordinate transformation. This model eliminates the problem of control coupling, which uses three variables instead of four magnetic poles to control three degrees of freedom. Next, we will further explore the characteristics of this approach by designing system controllers.

IV. Suspension Simulation

A. Cascade controller

According to the characteristics of the system, a cascade controller was designed. The motion of three degrees of freedom of the suspended platform was the target of the outer loop controller, and the rotation angle of the magnet was the control target of the inner loop controller. The control principle is shown in the Figure 8. Given the target position, the outer loop controller calculates the rotation angle of the magnet based on the error signal. Then, the inner loop controller processes the angle signal with the feedback signal from the encoder to change the input motor current. Thus, the rotation angle of each magnetic pole is controlled to make the platform move to the target position.

The cascade controller can improve the ability of overcoming disturbance and improve the control performance of the system in theory. In the control loop we designed, the outer loop controller and inner loop controller both are PD controller. The inner loop controller controls the rotation angle of four magnets, while the outer loop controller is acting on platform motion

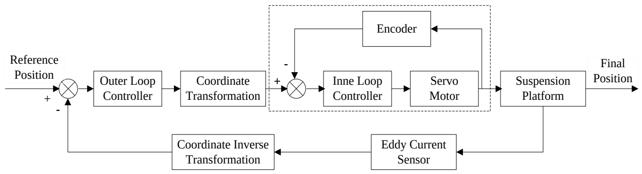


Figure 8. The schematic diagram of the rotation of the platform

B. *Simulation result*

In order to verify the effectiveness of the decoupling model and the cascade controller, the simulation block diagram is built. The system parameters are set according to the experimental platform, and the specific parameters are shown in Table 1. In the simulation block diagram, the parameters of PID controller are shown in Table 2.

TABLE I. THE SYSTEM PARAMETERS IN SIMULATION

m	The mass of suspension platform	9 kg
d_0	The air gap at the equilibrium position	4×10^{3} m
θ_0	The rotation angle at the equilibrium position	50°
Δd_f	Compensation coefficient of air gap.	1.6×10^{3} m
Δd_τ	Compensation coefficient of air gap	1.4×10^{2} m
k_m	Proportionality coefficient of attractive force	1.50×10^{-3} N/m^2
k_τ	Proportionality coefficient of rotational torque	-1.31×10^{3} Nm/m^2
k_i	Proportionality coefficient of torque of motor	1.2 Nm/A
J_α	Moment of inertia around X axis	0.11 kg · m^2
J_β	Moment of inertia around Y axis	0.18 kg · m^2
J	Moment of inertia of the disk PM	1.2×10^{-3} kg · m^2
$2e$	Distance between pole 1 and 2, pole 3 and 4	0.22 m
$2b$	Distance between pole 1 and 2, pole 3 and 4	0.36 m

TABLE II. THE PARAMETERS OF PID CONTROLLE

	the outer loop controller			The inner loop controller			
	z	α	β	1	2	3	4
P	25	45	48	14	14	14	14
I	170	350	420	150	150	150	150

In order to verify the decoupling characteristic of system, the simulation analysis of the step response of the system was carried out. In the simulation, total time was set to 10 s, and the position step signal was applied to each channel at different time. The response of the system is shown in Figure 9, where the 1mm step signal is applied for 0.5s in the z direction and it is removed after 1.5s. Finally, the system returns to its initial stable state. In this process, it could be proved that α, β is not affected by the parameter ref z. In the same way, the step signal is applied in the channel of α and β respectively and the other channel position signals are not affected. It shows that there is no control coupling problem in the system. It is feasible to realize decoupling by coordinate transformation.

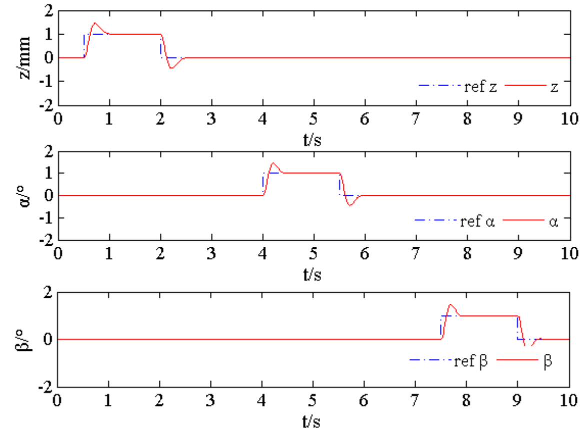


Figure 9. The step signal and position response of each channel

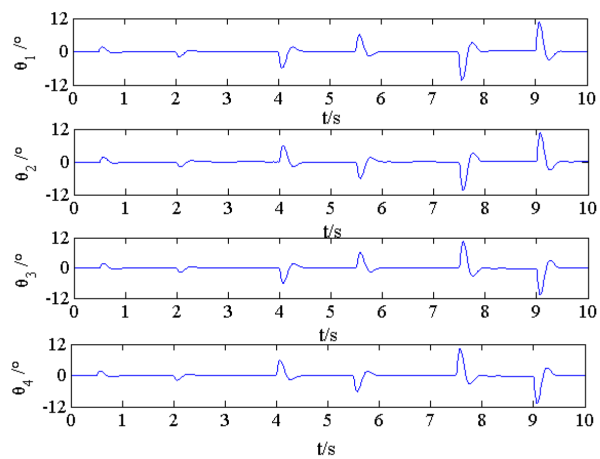


Figure 10. The rotation angle change of each magnetic pole

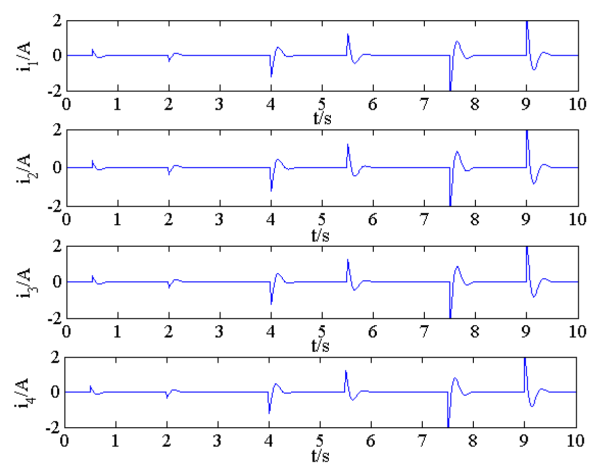


Figure 11 The current change of each magnetic pole

To investigate the relationship between the rotation angle of magnetic pole and the position of the suspension platform, changes sigals of angle and input current during the above mentioned process were collected. The results are shown in the Figure 10. It could be seen that angle of the four magnetic the step signal was applied in the channel of z. When the step signal was removed at 2s, change of the angle of the magnetic pole is opposite to that before. Similarly, when the step signal was applied to the α channel, angles of the magnetic pole 1 and 3 first decreased and then increased to the stable state, and the angles of magnetic pole 2 and the 4 first increased and then decreased to the stable state. When the step signal was applied to channel of β, the angle of pole 1 and pole 2 decreased first and then increased, and the angle of pole 3 and pole 4 increased first and then decreased.

In addition, the variation of magnetic pole current is consistent with the trend of angle change. The relationship between the position of platform and the angle of magnetic pole accords with the theoretical analysis. Through simulation, we can see that the magnetic poles can control the position of the suspension platform.

V. CONCLUSION

In this paper, the coordinate transformation method was used to establish the dynamic model of the permanent magnet suspension vehicle. Then, according to the characteristics of the system, a cascade control method was designed, which took the three degree of freedom control of the platform as the outer loop, and the change of the current and angle of the magnetic poles as the inner loop. Finally, the simulation was carried out according to parameters of the experiment prototype.

The simulation results show that the decoupling method of coordinate transformation can eliminate the control coupling of the platform and control the three degrees of freedom of the platform independently. When the step signal is applied to different channels, the response speed of the inner and outer loop can meet the requirements of the system, and the variation trend of the magnetic pole angle and current is consistent with the theoretical analysis. However, it can be seen from the simulation results that the response overshoot of the inner loop is very large when the signal is applied in the α and β channels, which is unfavorable to the stable suspension of the platform. This kind of device with platform structure is not suitable for permanent magnetic levitation to realize rotating motion.

In the near future, we will further verify the theoretical analysis and simulation results by experiment. It is also poles increased first and then decreased to a stable state when necessary to optimize the suspension characteristics and stiffness, so that it can be adapted to the actual work situation.

ACKNOWLEDGEMENTS

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