Suspension Characteristics of a Zero-Power Permanent Magnet Suspension System With Flux Path Control

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***Abstract*—A proposed permanent magnetic suspension using flux path control mainly consists of a disk permanent magnet, two pairs of F-type permalloy and a servo motor, and controls the suspension force by changing flux path, and the load on the motor shaft is eliminated due to its symmetric offset optimal structure to make the motor reach zero power output.**

In order to study the robustness of the system under external disturbances, this paper studies its suspension characteristics. Firstly, the structure and the suspension principle of the system are introduced. Secondly, the dynamic model is established, the controller of system is designed with the classic PD control method. Finally, the suspension characteristics of the system are studied through simulation and experiment. In the process of the experiment, the system is subjected to small step disturbance or small force disturbance, under the action of the real-time control system. The experimental results show that when the system is subjected to small step disturbance or small force disturbance in the process of the suspension, the suspended object will reach a new equilibrium position under the action of the real-time control system.

I. INTRODUCTIONS

Magnetic technology has a broad application prospect in the fields of mechanical industry, aerospace, vehicles[1-2], voice coil motors[3-4] and dust-free transmission. Magnetic technology is mainly divided into permanent magnet technology, electromagnetic technology and mixed magnetic technology. Among them, permanent magnet technology has the advantages of small size and low energy consumption, and electromagnetic technology has very good controllability[5-8]. Especially, the permanent magnet technology plays an important role in the precision instruments and dust-free environments. And the size of the permanent magnet attractive force mainly from three aspects, including the effective volume, air gap and magnetic permeability of the permanent magnet. On this basis, Sun et al.[9-12] studied the method of controlling the suspension force by changing the magnetic path, and proposed a permanent magnet suspension device with flux path control, which is mainly consisting of a disk permanent magnet, two pairs of F-shape core and a servo motor. And the suspension characteristics of the device are studied to prove that it has robustness.

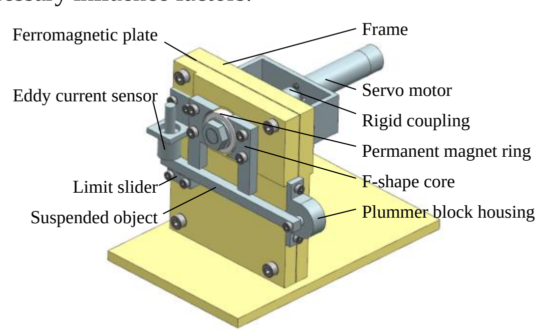
However, the research found that the device has a load torque generated on the motor shaft due to its structural characteristics, hence the device has a quasi-zero power characteristic. In order to reduce energy dissipation and improve motor output efficiency, an improved zero-power device with a symmetrical offset structure was proposed to eliminate the load torque and make the motor reach zero power output.

The main purpose of this paper is to study the suspension characteristics of the improved device and test its anti-jamming properties. The following is the composition of this paper. In section Ⅱ, the model and the suspension principle of the improved device are introduced. In section Ⅲ, the dynamic model is established according to the characteristics of the motion, and the controller is designed to control the suspension system. In section Ⅳ, based on the dynamic model and controller of the section Ⅲ, we set up a simulation block diagram to test the anti-jamming capability of the system in MATLAB/Simulink. In section Ⅴ, we introduce the experiment bench, the structure of the prototype, and analyze the experiment results of the prototype, in comparison with the simulation. The conclusion is in section Ⅵ.

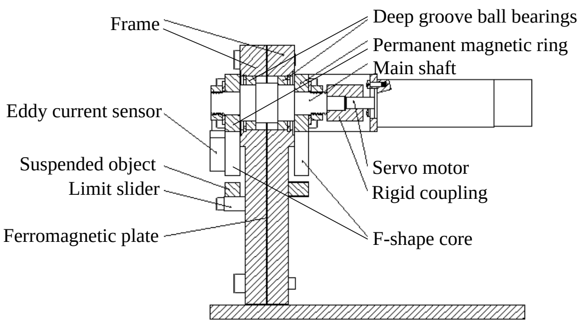
II. SUSPENSION DEVICE

A. *Model of Device*

As shown in Fig.1, the permanent magnet is fixed on the main shaft, and the main shaft is connected with the servo motor with the rigid coupling, and two pair of F-shaped core are placed on both sides of the permanent magnet; there is a ferromagnetic plate between two aluminum frame; one end of the suspended object is fixed through the bearing; an eddy current sensor is placed above the suspended object to measure the position of the suspended object. The advantage of the symmetrical structure is that it can be better to avoid unnecessary influence factors.



(a)Three-dimensional model diagram of the optimized device

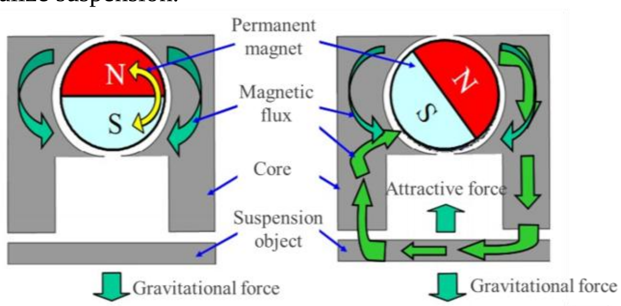


(b) Sectional view of the optimized device

Fig.1 Structure diagram of the device

B. *Principle of Suspension*

As shown in Fig. 2, the magnet rotated a certain angle, the facing angle of the N pole becomes bigger than the S pole in the right core, and that is reverse in the left core. Since that, the flux from the N pole in the right core is more than that in the left core. Some of the flux in the right core flow through the suspended object to the left core and is absorbed by the S pole. Consequently, there are some flux flowing through the suspended object, and the attractive force is generated to realize suspension.



(a)Initial state of system (b)The angle θ° of magnet

Fig.2 Principle of variable flux path control mechanism

III. DYNAMIC MODEL AND CONTROLLER

A. *Dynamic Model*

Based on the characteristics of the design, the suspended object does a single pendulum movement to minimize the impact of friction on the experiment. As shown in Fig. 3, where d is the distance between the sensor and the suspended object. When the suspended object deviates from the equilibrium position, the positive direction is vertical downward; H_1 is the distance between the sensor and the suspended object in horizontal position; H_2 is the distance between the core and the suspended object in horizontal position; d_1 is the distance between the suspended object and the left side core; d_2 is the distance between the suspended object and the right side core; θ is the rotation angle of the permanent magnet ring; φ is the angle between the horizontal direction and the suspended position in the equilibrium; L_1 is the distance between the left side core and the shaft; L_2 is the distance between the sensor and the shaft; L is the length of the suspended object.

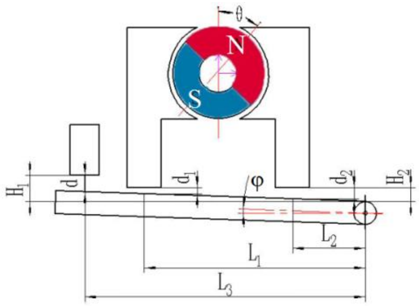


Fig.3 Model diagram of the system

The suspension force model of the system and the torque model of the permanent magnet are shown in equation (1) and equation (2), respectively:

$$f_m = k_m \frac{\sin^2\theta}{(d+\Delta d_f)^2} \tag{1}$$

where k_m is the suspension force coefficient, Δd_f is the leakage flux compensation coefficient of the suspension force at the air gap between the permanent magnet and the core.

$$\tau_j = k_\tau \frac{\sin 2\theta}{d+\Delta d_\tau} \tag{2}$$

where k_τ is the torque coefficient of the permanent magnet, and $\Delta d_\tau$is the leakage flux compensation coefficient of the torque at the air gap between the permanent magnet and the core.

When the system is in equilibrium position and applied the external force, the kinematics equation of the system is as follows:

$$J_1\ddot{\theta} = -c_1\dot{\theta} - \Delta\tau + k_t i \tag{3}$$

$$J_2\left(\frac{\dot d}{L_3}\right)' = -c_2\frac{\dot d}{L_3} + f_{m1}L_1 + f_{m2}L_2 - (mg+F)\frac{L}{2}\cos\varphi \tag{4}$$

where c_1 is the damping coefficient of the permanent magnet in the rotation direction; J_1 is the moment of inertia of the motor and the permanent magnet; J_2 is the moment of inertia of the suspension object; k_t is the torque coefficient of the servo motor; $\Delta\tau$ is the load torque of the motor; i is the input current for the servo motor, c_2 is the damping coefficient of the suspended object, f_{m1} is the suspension force of the left side core; f_{m2} is the suspension force of the right side core; and F is the external disturbance force acting on the entire suspended object.

When the system is in equilibrium and applied the external force, the linear differential equation is as follows:

$$J_1\Delta\ddot{\theta} = -c_1\Delta\dot{\theta} - a_1\Delta d - b_1\Delta\theta + k_t\Delta i \tag{5}$$

$$J_2\Delta\ddot{d} = -\frac{c_2}{L_3}\Delta\dot{d} - a_2\Delta d + b_2\Delta\theta - \frac{FL}{2}L_3\left((H_1-d_0)^2 + L_3^2\right)^{-\frac{1}{2}} \tag{6}$$

where $a_1 = \frac{L_1}{L_3}\frac{-k_\tau \sin 2\theta_0}{\left(d_1+\Delta d_\tau\right)^2} + \frac{L_2}{L_3}\frac{-k_\tau \sin 2\theta_0}{\left(d_2+\Delta d_\tau\right)^2}$,

$b_1 = \frac{2k_\tau \cos 2\theta_0}{d_1+\Delta d_\tau} + \frac{2k_\tau \cos 2\theta_0}{d_2+\Delta d_\tau} - \frac{4k_\tau \cos 2\theta_0}{d_3+\Delta d_\tau}$,

$a_2 = \frac{L_1^2}{L_3}\frac{2k_m \sin^2\theta_0}{\left(d_1+\Delta d_f\right)^3} + \frac{L_2^2}{L_3}\frac{2k_m \sin^2\theta_0}{\left(d_2+\Delta d_f\right)^3}$,

$b_2 = \frac{L_1 k_m \sin 2\theta_0}{\left(d_1+\Delta d_f\right)^2} + \frac{L_2 k_m \sin 2\theta_0}{\left(d_2+\Delta d_f\right)^2}$.

B. *Design Controller*

The position of the suspended object and the rotation angle of the motor in the permanent magnet suspension system are two main factors for the stability of the system, hence the controller controls these two variables.

According to the above requirements, the control system adopts two PD controllers that adjust the angle error and the position error, respectively. Finally the signals of position error and angle error are calculated by the PD controller as the input current of the motor. And the clockwise rotation of the permanent magnet is a positive direction. The structure of the control system is shown in Figure 4.

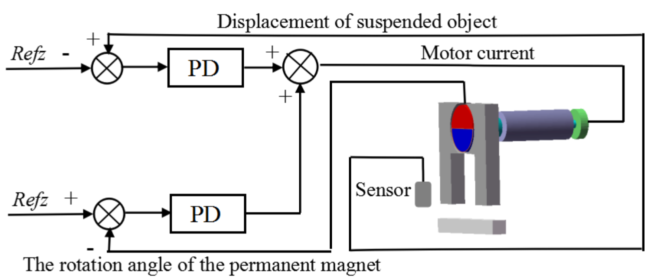


Fig.4 The structure of the control system

In order to verify the stability of the suspension, the simulations and the experiments were performed with the control method according to the structural parameters of the system in Tab. 1.

In the circuit for controlling the angle of the motor, since the influence of the angle feedback signal of the permanent magnet on the control is much greater than the position feedback signal of the suspended object and angle ring operates faster, the role of the position feedback signal can be ignored. The transfer function from the reference angle to the output angle is expressed as in equilibrium:

$$G_1(s) = \frac{\Delta\theta(s)}{\Delta\theta(s)'} = \frac{k_t k_{p1} + k_t k_{d1} s}{J_1 s^2 + \left(c_1 + k_t k_{d1}\right)s + k_t k_{p1} + b_1} \quad (7)$$

$\Delta\theta(s)$ and $\Delta\theta(s)'$ are approximately equal within a specific range of variation, hence the transfer function from the reference displacement to the output displacement is expressed as in equilibrium:

$$G_2(s) = \frac{\Delta d(s)}{\Delta d(s)'} = \frac{k_t b_2 L_3 k_{p2} + k_t b_2 L_3 k_{d2} s}{J_1 J_2 L_3 s^4 + w_0 s^3 + w_0 s^2 + w_1 s + w_2} \quad (8)$$

where $w_0 = J_1 c_2 + J_2 L_3 c_1$, $w_0 = -J_1 a_2 L_3 + J_2 L_3 b_1 + c_1 c_2$, $w_1 = -a_2 L_3 c_1 + b_1 c_2 + k_t b_2 L_3 k_{d2}$, $w_2 = k_t b_2 L_3 k_{p2} - a_2 L_3 b_1$. k_{p1} and k_{p2} are the proportional coefficient of the angle ring and the displacement ring, respectively; k_{d1} and k_{d2} are the derivative coefficient of the angle ring and the displacement ring, respectively.

IV. SYSTEM SIMULATION

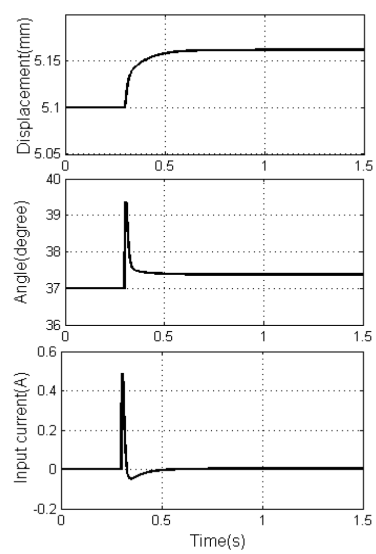
A. *Simulation Results*

Based on the analysis above, the simulation block diagram is built. And the parameters are established according with the parameters in Tab. 1.

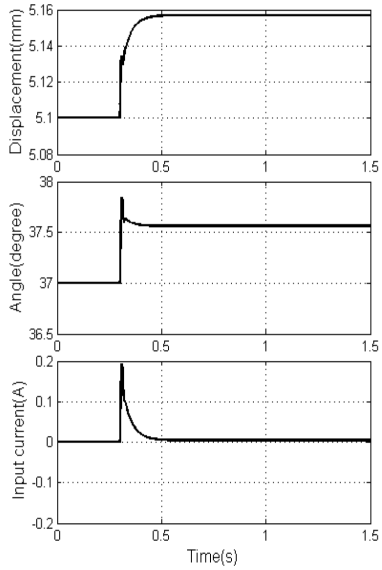
TABLE I. STRUCTURE PARAMETERS OF THE SYSTEM

	Parameter	Value
m	Quality of suspended object	0.142 kg
d_0	Equilibrium position of suspended object	5.1 mm
θ_0	Magnet angle in balance position	37degree
Δd_τ	The magnetic leakage compensation constant of the torque	14 mm
Δd_f	The magnetic leakage compensation constant of the suspension force	1.6 mm
J_1	The moment of inertia of the permanent magnet	1.856×10^{-5} kg•m^2
J_2	The moment of inertia of the suspended object	1.108×10^{-3} kg•m^2
k_t	The torque constant of the servo motor	0.69 Nm/A
k_τ	The torque constant of the permanent magnet	8.726×10^{-3} Nm^2
k_m	The constant of the suspension force	6.277×10^{-5} Nm^2

The matlab/simulink was used to analyze the anti-jamming simulation, and the displacement z of the suspension, the rotation angle θ of the permanent magnet, and the current i of the servo motor were respectively followed. The PD controller parameters: k_{p1}=180, k_{d1}=0.5, k_{p2}=31100, k_{d2}=1210, and the results obtained are shown in Fig. 5.



(a) The simulation result of step disturbance



(b) The simulation result of force disturbance
Fig.5 Simulation results of suspension system

As shown in Fig. 5, a displacement disturbance of 0.1 mm and a force disturbance of 0.1 N are respectively applied to the system at 0.3 seconds. When the system is subjected to external disturbances, the air gap of the suspension will be increased in the initial stage of the response, and the input current of the motor is quickly increased through the PD controller, which leads to the increase of the rotation angle of the permanent magnet to provide greater attractive force. Because the initial adjustment makes the current and the angle more than the stable value, in order to maintain the system stability, the rotation angle must be reduced. The input current of the motor decreases, and after a short adjustment, it finally makes the suspended object reach a new stable state. Simulation results show that the system has a certain degree of robustness.

V. ANALYSIS AND EXPERIMENS

A. *Experiment Set-up*

Based on the analysis above, the prototype is established according with the parameters in Tab. 1. In this experiment, the drive motor is an EC-max30 servo motor, its parameters: rated voltage is 12V, moment of inertia is 21.9 g•cm2, rated revolution speed is 6590 r/min, maximum speed is 7980 r/min. The eddy current displacement sensor adopts the EX-V series produced by Keeneshi. The material of the permanent magnet is NdFeB30, and the material of the "F"-shaped core and suspension is permalloy 1J85.

As shown in Fig. 6, the prototype has a symmetric offset optimal structure, which consists mainly of two radial magnetized permanent magnets, a servo motor containing a gear reducer and an encoder, two pair of F-shape core of high magnetically permeable material, a suspended object, an eddy current sensor and a bearing bracket. The material of the F-shaped core is permalloy, and the material of the permanent magnet is NdFeB30, its the parameters: the outer diameter is 40mm, the inner diameter is 16mm, the thickness is 10mm. The air gap length is 2mm between the F-shape core and the magnet. In order to verify the anti-interference characteristics of the system, a dSPACE real-time controller was used to build the experiment bench. And the permalloy material can enhance the magnetic permeability of the suspended object; the iron plate is used to monitor the position of the suspended object in real time.

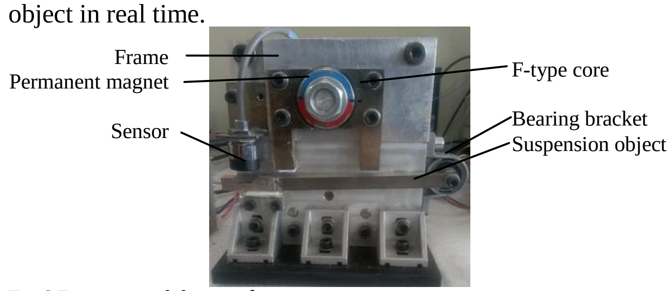
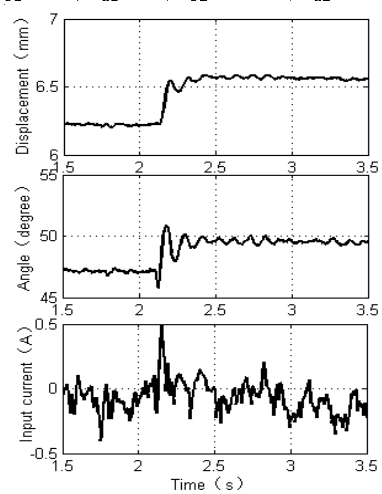


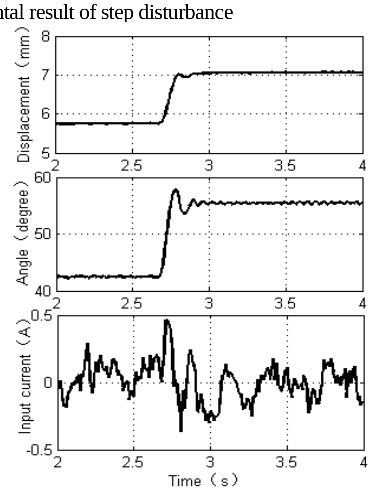
Fig.6 Experimental device of suspension system

B. *Experiment Results*

When the system is subjected to small step disturbance or small force disturbance, under the action of the real-time control system and PD controller, the experimental results are shown in the Fig.7. Firstly, the suspended object is in steady suspension state, Fig. 7(a) shows the results of loading the suspension object with an amplitude signal of 0.1 mm, and Fig. 7(b) shows the results of loading the suspended object with the direction downward force of 0.1N. The PD controller parameters: k_{p1}=180, k_{d1}=0.5, k_{p2}=31100, k_{d2}=1210.



(a)The experimental result of step disturbance



(b)The experimental result of force disturbance
Fig.7 Experimental results of suspension system

When the system is subjected to displacement disturbance and external force disturbance, the suspended object will be directly affected and the air gap will increase. And the increase of the air gap will result in the attraction force less than the gravity and make the system unbalanced. At this time, the PD controller begins to adjust to increase the current of the input motor, which increases the rotation angle of the permanent magnet to provide greater attraction. Finally, the system regains a stable state in a new equilibrium position. However, the vibration of the suspended object is serious in the experiment of displacement disturbance, and it can quickly reach stability in the experiment of external force disturbance. The reason for this phenomenon is that the force applied to the suspended object is equivalent to increasing the quality of the suspended object, which results in smaller acceleration. The experiment results are consistent with the simulation results. However, due to the influence of friction, the reaction time and the equilibrium position are deviated compared with the simulation results. Finally, the simulation and test results show that the system has certain robustness under the external disturbance.

VI. CONCLUSIONS

In this paper we present the model, the kinematics equation, the controller design, simulation and experimental results of a zero-power permanent magnet suspension system with flux path control, and investigate the suspension characteristics on the system. The results of our study confirm that a better suspension characteristic will resist the external disturbance while exerting the disturbance. The results from both theoretical simulations and practical experiments show when the system is subjected to external disturbances, the system can quickly adjust through the PD controller and timely track the position signals, and prove the feasibility of the suspension. Therefore, the system has certain robustness under the external disturbance. However, it is suggested that further research such as the friction of the suspension object and the control method would be necessary to complement this study improving the suspension characteristics of the system.

ACKNOWLEDGEMENTS

This research is supported by Liaoning Province innovative talents in Colleges and Universities support program (No. LR2017036), Doctoral Scientific Research Foundation of Liaoning Province (No. 20170520177), and Liaoning province Talents Project (No. 2015-47).

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