2 DOF Maglev System with Permanent Magnet Motion Control

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Abstract: A new type of 2-DOF(degree of freedom) magnetic suspension system for multi-DOF suspension is proposed. This paper will deal with all aspects of design. Firstly, the principle of the levitation system and typical reluctance control methods are described. Secondly, an experimental device is introduced. Motion model is built and analyzed. Thirdly, a controller of this system is designed. Finally, some experiments results are shown.

Keywords: permanent magnet, magnetic suspension system, linear control, 2 DOF.

1. Introduction

There is a growing demand for magnetic suspension, especially in the field of high accuracy multi-dimensional positioning[1]. Our motivation is using magnetic suspension technology to develop a permanent magnet suspension system. It can realize noncontact remote control and micromanipulation. It can be applied in such fields in which ultra-clean environment is needed to avoid sample contamination, such as semiconductor processing, biotechnology experiments, especially, when the object is moved with micro displacement.

There are many kinds of maglev system.[2)-3)] In this system, we propose a novel active maglev system with permanent magnets and a motion control mechanism in place of electromagnets and a current control mechanism. The force of permanent magnets are used for levitation and controlled by adjusting the reluctance of the magnetic circuit. Using permanent magnets, the features of this system are effective for saving energy, avoiding heat generation, no mechanical wearing and dust free[4)-6)].

In this investigation, we study the 2 DOF suspension system that manipulate the object in the vertical plane, as a one step of multi-DOF micromanipulation. The principle of suspension system is explained and a 2 DOF system is introduced.

2. Principle of Suspension System

A outline of proposed suspension system with a permanent magnet and linear actuator is shown in Fig.1. A ferromagnetic body is suspended by an attractive force from a permanent magnet, which is driven by an actuator, positioned above. The direction of levitation is vertical, and the magnet and the object move only in this direction. The equilibrium position of the ferromagnetic body is determined by means of a balance between the gravity force and the magnet force.

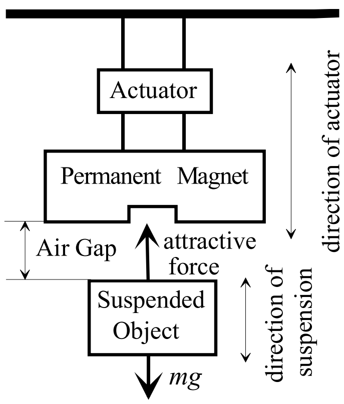

Fig.1 Outline of suspension

If the actuator does not actively control the magnet's position, the levitated object will either fall or adhere to the magnet. However servo-control of the actuator can make this system stable. Because there is a smaller attractive force for a larger air gap between the permanent magnet and object, the actuator drives the magnet upwards in response to object movement from its equilibrium position towards the magnet. Similarly, the actuator drives the magnet downwards in response to object movement away from the magnet. In this way, the object can be stably suspended without contact. In comparison to the electrical control method of electromagnetic suspension systems, this system is a mechanical control maglev system[7)]

3. 2-DOF Suspension System

3-1 Experimental Setup

Based on the principle, the prototype of system is built. It is shown in Fig.2. From the picture we can see that there are three voice coil actuators which drive the three permanent magnets respectively. Motion of the magnet is sensed by gap sensor. There are two motion directions in this system, vertical motion and horizontal motion. Here, we only consider the horizontal motion. Assume that the vertical motion does not affect the horizontal motion.

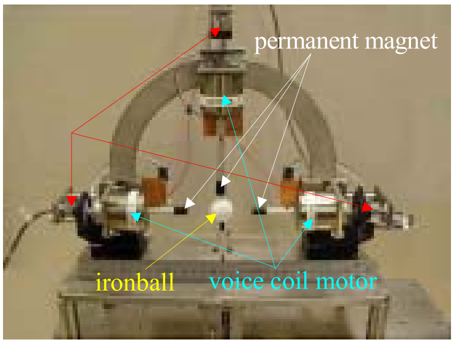

Fig.2. The prototype of system

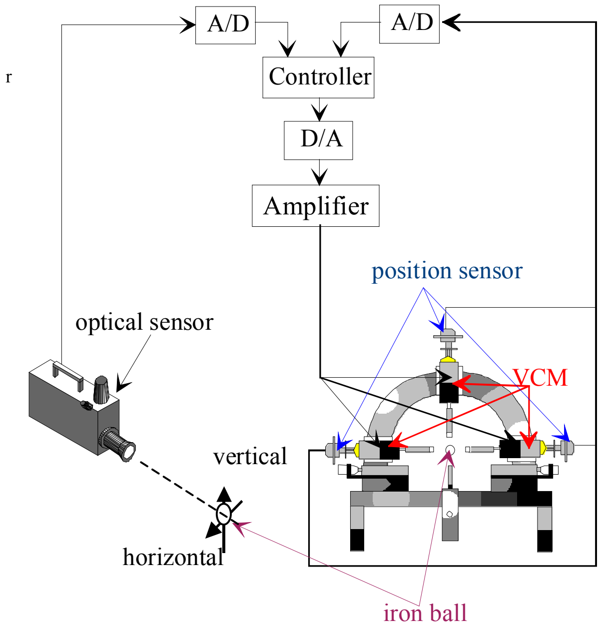

Fig.3. The configuration of system

The system configuration is show by Fig.3. The iron ball has a diameter of 25 mm and a weight of 63 g. the permanent magnets have cylindrical shape with a diameter of 8 mm and a length of 10 mm. The moving part with the magnet has a weight of 375 g. The actuator has a stoke length of 15 mm and a rated propulsive force of 10 N at a coil current of 2 A. The gap sensor sensing the permanent magnet movement, which is located behind the actuator, is eddy current type and has a sensing range of 10 mm and a resolution of 10 µm. The movement of the iron ball is sensed by 2 axes photo sensor and has a sensing range of 20 mm and a resolution of 5 µm. Controller is a digital DSP controller with 12 bit resolution A/D converters and 16 bits D/A converter.

3-2 Model Analysis

The motions of the iron ball and the magnets divide into two directions, vertical and horizontal, movement. It is consumed that two motions are independent of each other. The analysis of vertical motion has been already investigated [8]. Here, the horizontal motion, which involves the motions of an iron ball and two permanent magnets driven by actuators, are mainly investigated. Horizontal motion model is shown in Fig.4.

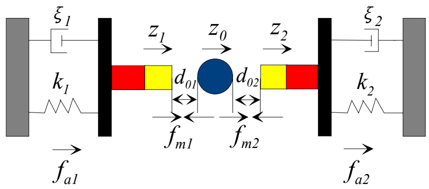

Fig.4 Horizontal motion model of system

As can be seen, the symbols used in the following study are:

- z_0: displacement of the iron ball,
- z_1,z_2: displacements of the left and right permanent magnets,
- m_0: mass of the iron ball,
- m_1,m_2: mass of the magnets,
- f_{a1},f_{a2}: generating forces of the left and right actuators,
- f_{m1},f_{m2}: attractive forces between the ball and the magnet,
- d_{01},d_{02}: the initial left and right side air gap lengths about the ball. They are constants.
- k_{m1} ,k_{m2}: the coefficients of magnetic fields.
- k_1,k_2: the spring coefficients of the left and right actuators,
- ξ_1, ξ_2: the damping coefficients of the left and right actuators.

The displacements and forces are considered positive when they act in the right side direction. And it is consumed that the friction of the guide of the actuator and viscosity of the air are negligible. The equations of the motion of the suspended object and the magnets are:

$$m_0\ddot{z}_0 = f_{m2} - f_{m1} \qquad (1)$$

$$m_1\ddot{z}_1 = -\xi_1\dot{z}_1 - k_1 z_1 + f_{m1} + f_{a1} \qquad (2)$$

$$m_2\ddot{z}_2 = -\xi_2\dot{z}_2 - k_2 z_2 - f_{m2} + f_{a2} \qquad (3)$$

where $f_{m1}=k_{m1}/d_{01}^2$, $f_{m2}=k_{m2}/d_{02}^2$. Due to the relationship between magnetic force and the air gap is nonlinear, the equations, (1), (2) and (3) must be linearized. After linearizing, the horizontal motions can be expressed by the following state space model:

$$\dot{x} = Ax + bu \qquad (4)$$

$$y = cx \qquad (5)$$

In the model, the magnets are independent that is, the two magnets are driven via two different amplifiers respectively, and f_{a1} and f_{a2} are the system inputs. f_{a1} is not equal to f_{a2} and m_1 is not equal to m_2 then the system has two inputs, i.e. this system is two forces input system. Where

$$x = \begin{pmatrix} \dot{z}_0 & z_0 & \dot{z}_1 & z_1 & \dot{z}_2 & z_2 \end{pmatrix}'$$

$$b = \begin{pmatrix} 0 & 0 & 1/m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/m_2 & 0 \end{pmatrix}'$$

$$c = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$u = \begin{pmatrix} f_{a1} & f_{a2} \end{pmatrix}'$$

Since both of the rank controllability matrix of system and the determinant of the observability matrix are not equal to 0 the system is controllable and observable.[9)]

4. Controller Design

In terms of linear control theory, due to the system is controlled and observed, the LQR (linear quadratic regulator) full state feedback control law can be used to design the controller of this system.

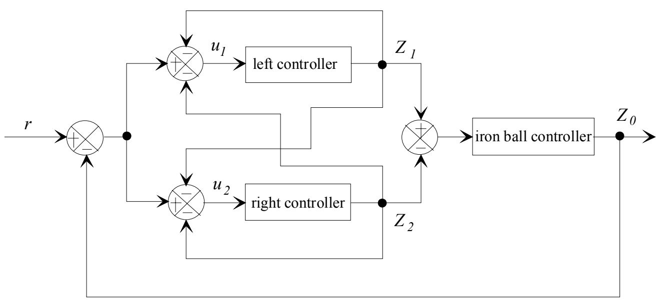

Fig.5 The control system block diagram

The control system block diagram is shown in Fig.5. In this diagram

r is the reference input of system;

u_1 , u_2 are the inputs of system;

z_0, z_1, z_2 are the iron ball's position, left magnet's position and right magnet's position respectively. they are the outputs of system.

The relationship among the iron ball's position and the two permanent magnets' position is very complicated. From this diagram we can see that the iron ball's position can be controlled via control the two permanent magnets' position. In the verse, the iron ball's position can be used to control the two permanents' position, meanwhile, the two permanent magnets' position effect each other. The reference signal and z_0 is divided into two parts to control z_1 and z_2.

Due to z_0, z_1, z_2 are the outputs, this system is the output feedback system. The cost function is:

$$J = \frac{1}{2}\int_0^t [x^T Qx + u^T Ru]dt \qquad (6)$$

In this equation, Q is the state weighting matrix and R is the input weighting matrix.

$$K=R^{-1}b^{T}P \qquad (7)$$

P is the solution of Riccati Equation. After choose the states weighting matrix Q and input weighting matrix R and solve the Riccati Equation, the feedback gains of system K can be gotten.[10)]

5. Experiment Examination

Based on the different feedback gain, we examined the numerical simulation and the experiment of step response.

5-1 Simulation examination

The initial air gap d_{01}=d_{02}= 8 mm and the step input of 0.5 mm is added as the reference input When

$$K_1 = \begin{pmatrix} 863.5064 & 22.9941 & -389.4165 & -1.5585 & -557.8677 & -0.0677 \\ -792.127 & -21.1031 & 58.2775 & 0.0691 & 377.8172 & 1.5359 \end{pmatrix}$$

the numerical simulation result is shown in Fig.6, and when

$$_2 = \begin{pmatrix} 489.8996 & 11.7752 & -173.1873 & -1.2769 & -57.7570 & -0.0825 \\ -449.9808 & -10.8241 & 58.0807 & 0.0842 & 161.8085 & 1.2558 \end{pmatrix}$$

the numerical simulation result is shown in Fig.7. Compare with these two Figures, we can find that when the feedback gain is reduced the over shoot of the response curve is increase, but the rising time is decrease. From the simulation result we can also see that the iron ball can be moved through moving the two permanents magnets.

5-2 Experiment examination

After simulation, Experimental examination was carried out on the system and 2 DOF magnetic levitation succeeded.

Initial position is set as the ball is located in the center of the magnet. The air gap between the horizontal magnets was set to 8 mm through adjust the position of the horizontal magnets. A step input of 1 mm was added to the signal of the reference of the ball. Using above feedback gain, the results of step response were recorded in Fig.8 and Fig.9 respectively. From them, we can see that the results of experimental examination conform on the simulation examination. The correspondency between numerical simulation and experimental examination results improves that the model in Fig.4. is correct.

6. Conclusion

A novel active maglev system was propsed. In the proposed system, bearing force is controlled by a mechanical method in which the air gap between a permanent and suspended object is varied by an actuator.

The prototype of 2-DOF suspension system has been constructed. From this prototype, the horizontal model is gotten. After analyze the model, the system is controlled and observed. A LQR controller has been designed. Simulation results and experiment examination have been gotten. On the experiment examinations, it was verified that the iron ball can be suspended without any mechanical contact and can be moved at the horizontal direction.

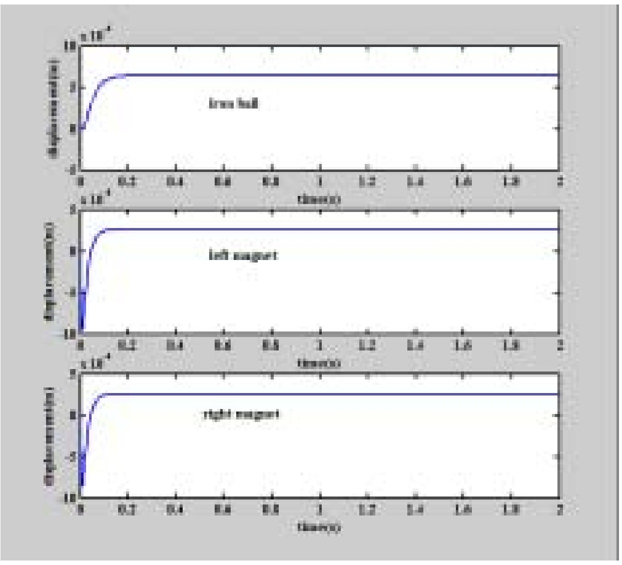

Fig.6. Step response of numerical simulation of K_1

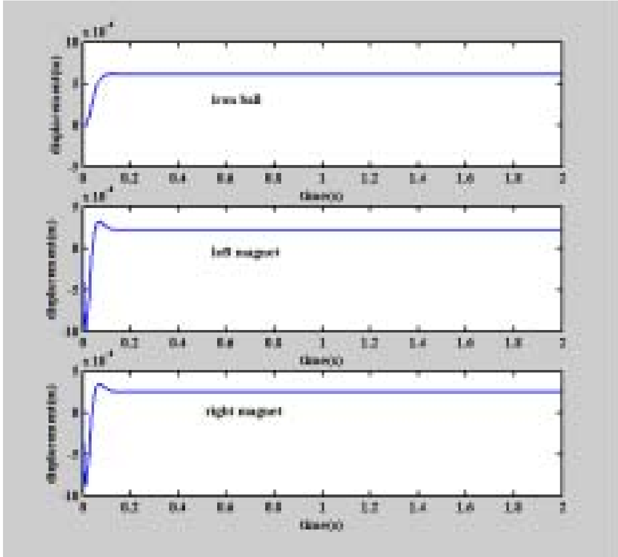

Fig.7. Step response of experiment examination of K_2

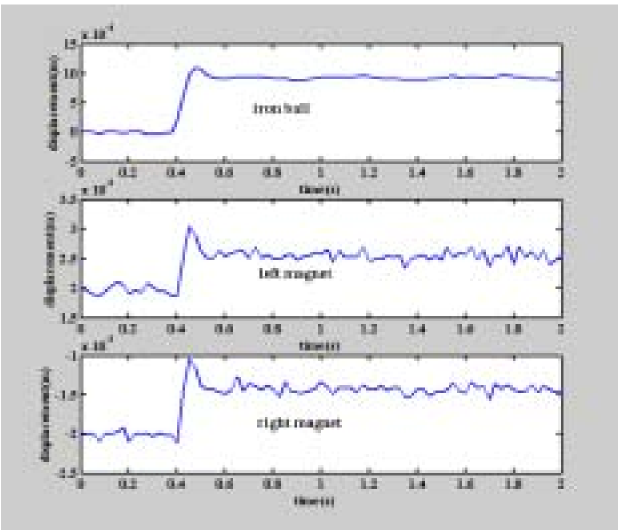

Fig.8. Step response of experimental examination of K_1

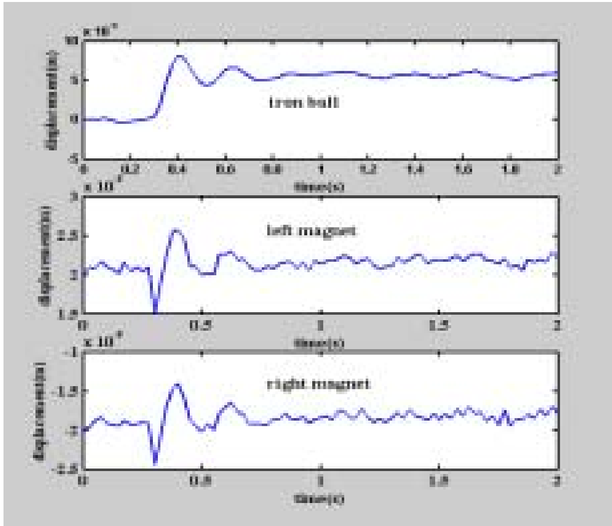

Fig.9 Step response of experimental examination of K_2

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