第14回インテリジェント・システム・シンポジウム

Fuzzy, Artificial Intelligence, Neural Networks and
Computational Intelligence

FAN Symposium '04 in Kochi

講 演 論 文 集

2004年10月9日(土)～10日(日)

高知工科大学

主催:　日本知能情報ファジィ学会
共催:　計測自動制御学会、電気学会、システム制御情報学会、
電子情報通信学会、人工知能学会、日本神経回路学会、
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日本AEM学会、高速信号処理応用技術学会
後援:　高知工科大学、高知県

2-105 2-DOF PERMANENT MAGLEV SYSTEM WITH LQR CONTROLLER

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A new type of 2-DOF (degree of freedom) magnetic levitation systems for multi-DOF levitation is proposed. In this system, the force of permanent magnets are used for levitation and controlled by adjusting the reluctance of the magnetic circuit. Firstly, the principle of suspension system is explained and a 2 DOF maglev system is introduced. Secondly, an experimental device based on the principle is introduced. Thirdly, the feasibility of this system is considered with linear control theory. Finally, LQR controller is introduced to control this system.

Key Words: 2-DOF maglev system, LQR, linear control, permanent magnets

1. Introduction

Magnetic suspension system that controls attractive forces by adjusting the air gap has been developed [(1)]. The feature of this suspension mechanism is use of permanent magnets and linear actuators. To control supporting forces, the system adjusts air gap lengths by permanent magnet movements. There were some 1DOF developments of this suspension mechanism [(2)-(4)].

In this paper, 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. Some experimental results are shown.

2. Principle of suspension system

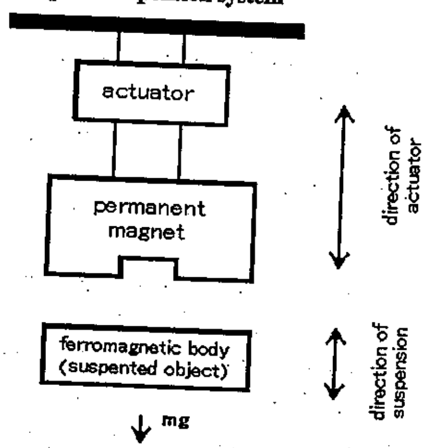

Figure 1. Outline of suspension mechanism

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

3. 2 DOF suspension system

3.1 Experimental setup

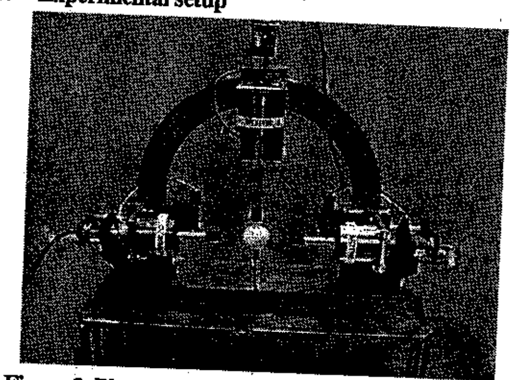

Figure 2. Photograph of the prototype of suspension system

A photograph of a prototype 2 DOF suspension system is shown in Fig. 2. There are three voice coil actuators which drive permanent magnets. The actuators are installed to semicircle rail and directions of the magnet movements can be adjusted bye the installed position. The suspended object is an iron ball, and is manipulated by the movements of the three magnets. The movements of the magnets and the iron ball are sensed by the gap sensors and the photo sensor, respectively.

3.2 Modeling and theoretic analysis of system

As shown in Fig. 2, it is considered that the motions of the iron ball and the magnets divide into the vertical and the horizontal direction movement. It is consumed that two motions are individual each other. The analysis of vertical motion has been already investigated [(1)]. Here, the horizontal motions which involve the motions of an iron ball and two permanent magnets driven by actuators are mainly investigated.

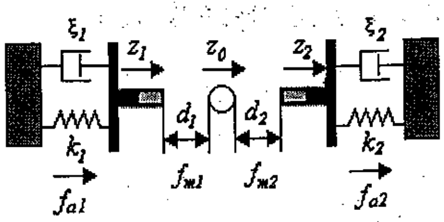

Figure 3. The modal of horizontal motion

Fig. 3. shows the modal of horizontal motion of system. As can be seen, the symbols which are 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_1, d_2: left and right side air gap lengths about the ball.

k_{m1}, k_{m2}: the coefficients of magnetic fields.

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

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

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

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

where $f_{m1}=k_{m1}/d_1^2, f_{m2}=k_{m2}/d_2^2$.

After linearization, the horizontal motions can be expressed by the following state space model:

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

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

In the model of Fig.3., the magnets are independent and f_{a1} and f_{a2} are the system inputs. If 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.

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

$$A = \begin{bmatrix} 0 & -\frac{k_{m1}}{m_0 d_{01}^3} - \frac{k_{m2}}{m_0 d_{02}^3} & 0 & -\frac{k_{m1}}{m_0 d_{01}^3} & 0 & \frac{k_{m2}}{m_0 d_{02}^3} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{k_{m1}}{m_1 d_{01}^3} & -\frac{\xi_1}{m_1} & -\frac{k_{m1}}{m_1 d_{01}^3} - \frac{k_1}{m_1} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \frac{k_{m2}}{m_2 d_{02}^3} & 0 & 0 & -\frac{\xi_2}{m_2} & -\frac{k_{m2}}{m_2 d_{02}^3} - \frac{k_2}{m_2} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

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

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

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

Where the rank of controllability matrix

$Rank\begin{bmatrix} b & Ab & A^2b & A^3b & A^4b & A^5b \end{bmatrix} = 6$, is full rank, so the system is controllable. At the meanwhile, the rank of the observability matrix

$Rank\begin{bmatrix} c' & A'c' & (A')^2c' & (A')^3c' & (A')^4c' & (A')^5c' \end{bmatrix} = 6$,

is full rank also, so the system is observable

3.3 Controller design

There many ways to design a controller such as H_2, H_∞ and LQR feedback control methods etc. Here we choice the LQR control law to design the controller of this system.

In this system, due to the plant is controllable and observable, by means of LQR control law $J = \frac{1}{2}\int_0^t [x^T Qx + u^T Ru]dt$, when we keep Q and R positive and constant, using MATLAB, we can get feedback gain easily. Under such condition, the stability of system need not considered.

4. Conclusion

Aiming noncontact micromanipulation, a 2 DOF magnetically suspended system has been investigated. The following are conclusions of this paper. 2 DOF prototype suspension system has been made. To make a model of the system, the controllability and observability have been analyzed with linear control theory. As the result of the analysis, it has been found that the system is controllable and observable. By means of LQR control law to design the controller, the system is stable.

Acknowledgement

The authors would like to acknowledge Mr. Keiji Masaki for his helpful cooperation. A part of this work is financially supported by the Grant-in-Aid for Scientific Research (B)(2)(12450099) of Japan Society for the Promotion of Science.

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