Suspended Object Rotation Mechanism with Permanent Magnet Motion Control

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Tianshi Cui * Koichi Oka ** Yusuke Fujiwara ***

Department of Intelligent Mechanical Systems Engineering,
Kochi University of Technology
185 Miyanokuchi, Tosayamada-town, Kami-shi, Kochi 782-8502

E-mail: * tscui@neau.edu.cn, ** oka.koichi@kochi-tech.ac.jp
***095226a@gs.kochi-tech.ac.jp

要約：非接触浮上している対象物を回転させる機構を提案する．提案した機構の特徴は，浮上および回転を永久磁石とアクチュエータを用いた機械的な制御により実現している点である．まず，浮上原理を説明し，回転機構のための試作装置の紹介を行う．次に試作装置のモデル化を行い，数値シミュレーションによって本方式の実現性を確認する．最後に試作装置を用いて実験を行った結果，浮上および回転に成功したことを報告する．以上のことによって本提案の有用性を確認する．

Abstract: A new type of magnetic suspension system, in which the suspended object can be moved in the vertical and horizontal plan, is proposed. This paper describes the development of this system. Based on the principle of the magnetic levitation system, an experimental device is constructed. Through control the movement of permanent magnets with linear actuators, we can make the suspended object suspend and rotate along the suspension axis.

1 Introduction

So far, for avoid sample contamination there are more and more requirements of environment in science experiments and manufacturing. Hence, noncontact manipulation is being developed. Compare with contact manipulation, there are no stain, less friction and elimination of lubricants in noncontact manipulation. Our motivation is using magnetic suspension technology to develop a permanent magnet suspension system. It can realize noncontact 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 and biotechnology experiments, etc.

There are many kinds of maglev system(1), (2). In this paper, 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(3)-(5).

In this investigation, a suspension system in which the suspended object is manipulated in the horizontal plane is built. It makes the suspended object rotate along the suspension axis. In this paper, the principle of suspension and rotation of this system is explained and experimental examination is performed.

2 Suspension of Object

2.1 Suspension principle

An outline of the proposed suspension system with a permanent magnet and linear actuator is shown in Fig.1. A ferromagnetic body is suspended with an attractive force from a permanent magnet which is driven by an actuator positioned above. The direction of levitation is vertical; 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.

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(6).

2.2 Suspension Experiment

Fig.2 shows the configuration diagram of suspension system. The gap sensor located upper of the actuator senses the permanent magnet movement. It is an eddy current type and has a sensing range of 10 (mm) and

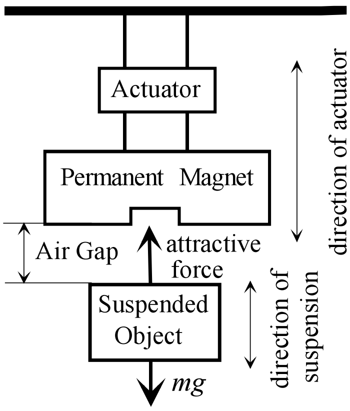

Fig.1 Outline of suspension

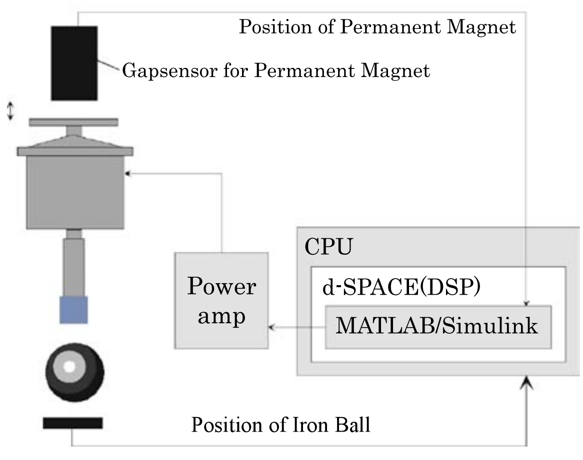

Fig. 2 Configuration of suspension system

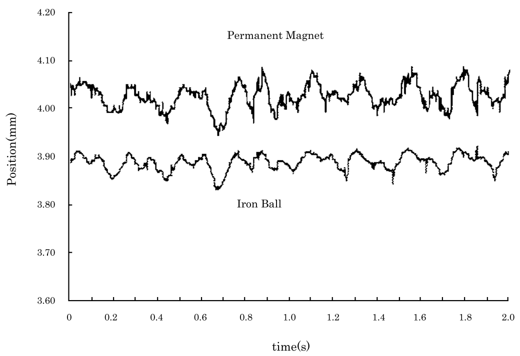

Fig. 3 Movement of iron ball and magnet during suspension

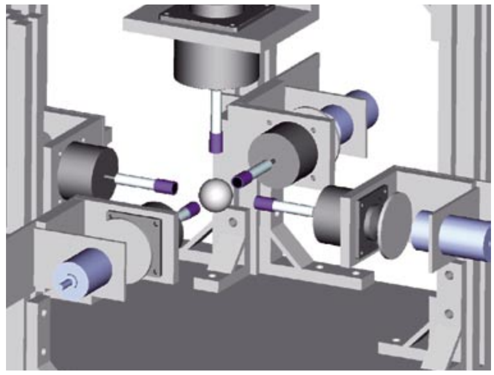

Fig. 4 Illustration of Prototype

a resolution of 10 (μm). The movement of the iron ball is sensed also by means of an eddy current sensor which is indicated as a bar under the ball. Its resolution is 5(μm). Controller is a digital DSP controller with 12 bit resolution A/D converters and 16 bits D/A converter. Through A/D converters, two sensors' signal are converted to digital value and input into DSP Controller. Controller computes the current for VCM. Through D/A converter, the currents is converted to analog value and input into current amplifier to control the movement of magnet.

When the feedback gain is applied, the iron ball is suspended successfully. The result is shown in Fig. 3. This figure is a time history of the displacement of iron ball and magnet in which the sample time is 0.005(s), and the interval is 2 (s).

3 Rotation Mechanism

3.1 Experimental Setup

Based on the principle, the prototype of system is built. Fig.4 is the illustration of the prototype. The iron ball is suspended in the central position of prototype. The VCM actuators are fixed at the point that has the same distance to the center of mechanism.
From the figure we can see that there are five VCM actuators, which drive the five permanent magnets respectively. The position of magnets is sensed by means of eddy current sensors. When the iron ball is suspended, through control the motion of upper magnet the height of iron ball can be adjusted to make the iron ball and four horizontal magnets in the same horizontal plane. And through control the approaching order of four horizontal magnets we can make the iron ball rotate along suspension axis.

3.2 Rotation principle

The purpose of this investigation is to make a rotation control mechanism in which the suspended object is rotated along the suspension axis when it is suspended. The image of rotation is shown in Fig.5. For simplification, only the magnets that are located in the horizontal plane and iron ball are shown in it. This figure is a plan form. From it we can see the location of four magnets and iron ball. The iron ball is located in the center position, and four magnets are located perpendicularly each other around the iron ball in the horizontal plane.

Due to the suspended object is an iron ball, which is a ferromagnetic substance, there is remanent magnetism on the surface of it.

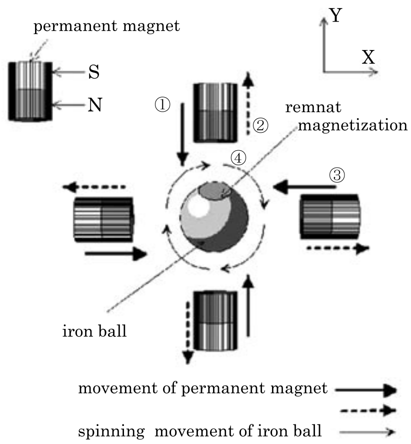

Fig. 5 Strategy of rotation

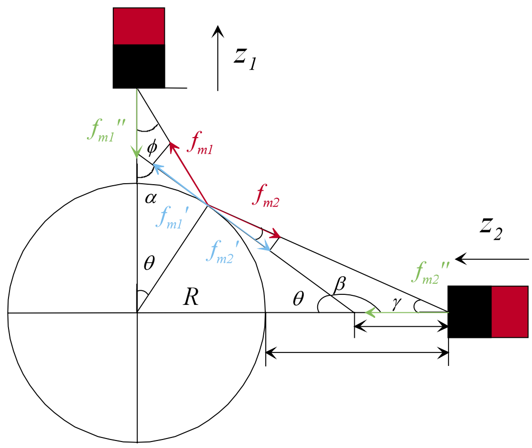

Fig. 6 Rotation model

However, when the iron ball is suspended, the influence of remanent magnetism is mostly in the vertical direction of suspension. It keeps the iron ball suspended. When the magnet located in horizontal approaches the iron ball, there is a magnetization point on the surface of iron ball facing the approaching magnet. And when this magnet withdraws and the next magnet approaches, the approaching magnet will attractive the magnetization point. When the magnet approaches the iron ball alternatively, the iron ball can be rotated along the suspension axis. In Fig. 5, the approaching order of magnets is magnet a, b, c and d. This is one circle of approaching.

3.3 Rotation model analysis

From the rotation principle and prototype of this system, a rotation model is created. It is shown in Fig. 6. In this model, only two magnets are acting on the suspended object. The influences of other two magnets can be neglected because the air gap length is large enough.

From this figure, the rotation equation of the iron ball and permanent magnet can be obtained.

$$I\ddot{\theta} = (f_{m2}' - f_{m1}')r \tag{10}$$

$$m_1\Delta\ddot{z}_1 = f_{a1}\sin(\varpi_1 t - \frac{\pi}{2}) + f_{m1}'' \tag{11}$$

$$m_2\Delta\ddot{z}_2 = f_{a2}\sin(\varpi_2 t - \frac{\pi}{2}) + f_{m2}'' \tag{12}$$

$$m_3\Delta\ddot{z}_3 = f_{a3}\sin(\varpi_3 t - \pi) + f_{m3}'' \tag{13}$$

$$m_4\Delta\ddot{z}_4 = f_{a4}\sin(\varpi_4 t - \frac{3\pi}{2}) + f_{m4}'' \tag{14}$$

3.3 Simulation examination of rotation

For examining the principle of rotation, a simulation has been done. The result is shown in Fig. 7. From this figure, it can be seen that when the magnets moved periodically towards the iron ball, the iron ball can be rotated along the suspension axis, but the rotation speed is not uniform. It is changed periodically. In a period of the movement of the magnets the rotation speed is varied four periods.

4 Experiment of Rotation

4.1 Configuration of rotation system

Fig.8 shows the system of rotation mechanism. Only one horizontal magnet motion control is shown in this figure. The other three magnets' motion has the same control system with this figure. The magnet

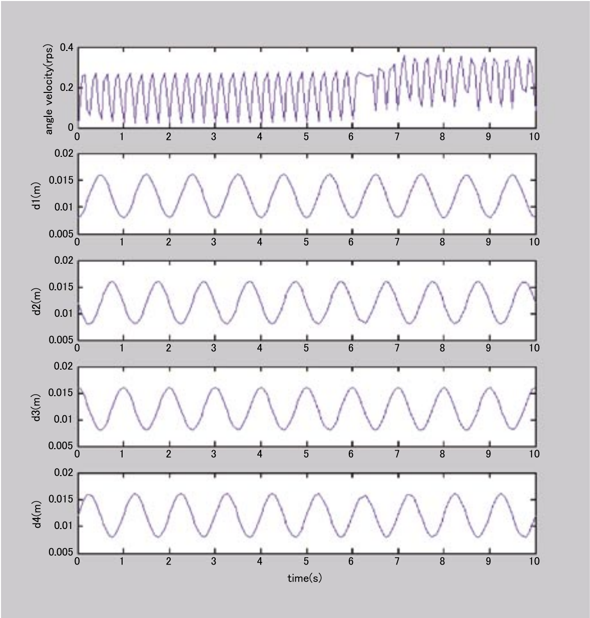

Fig. 7 Simulation result of rotation

position is sensed via an eddy current sensor. The sensor's signal is converted to digital signal through A/D converter and then is input into DSP controller. Controller computes the current for VCM and the signal is converted into analog value through D/A converter, and then the value is input a current amplifier to drive the VCM. The magnet is driven by VCM actuator to move straightly towards or away to the iron ball. In this investigation, the suspension and rotation control are independent each other.

Fig. 9 shows the control system of experiment. In this system, four input signals have the same frequency ω , and the phase difference of each VCM is $\pi/2$ (rad) one by one. This phase difference keeps the approaching order of magnets.

4.2 Experimental result

The experiment is carried out with the control system. The iron ball is rotated successfully. The frequency of reference input signal is 0.5 Hz, and the rotation velocity

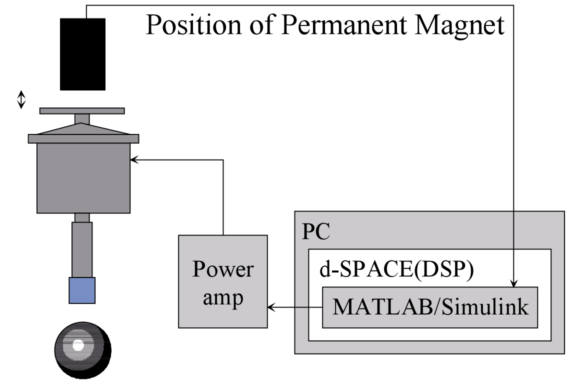

Fig.8 Configuration of rotation system (1/4)

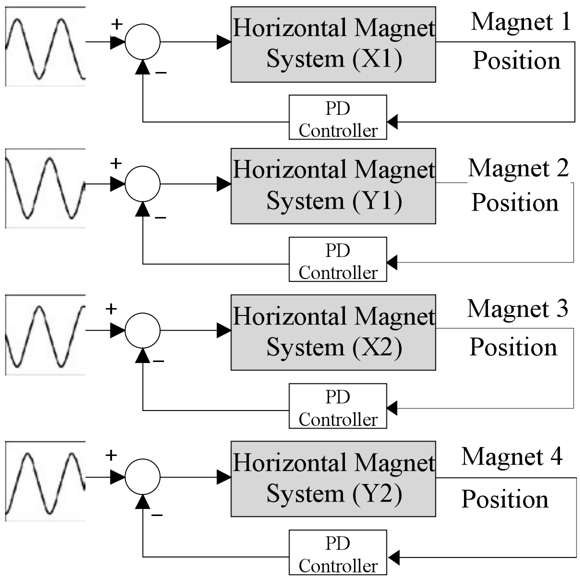

Fig. 9 Control diagram of rotation

time history is shown in Fig. 10. The rotation velocity is measured by means of a laser feed monitor.

From the figure, we can see that the average rotation velocity of the iron ball is about 0.5 rps, but it is not uniform. That is caused by open loop control and weak remanent on the surface of the iron ball. The cycle of magnet movement is difficult to select when the rotation is started. A feed back control of the iron ball angle is necessary for improving the rotation.

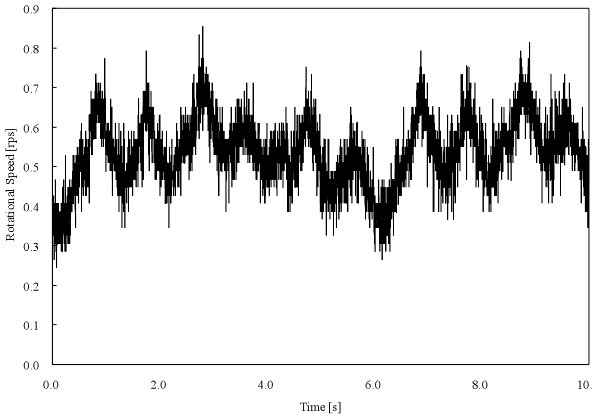

Fig. 10 Experimental result of rotation speed

5 Conclusion

As the one step of the development of the noncontact manipulation mechanism, a noncontact rotation mechanism with linear actuators and permanent magnets has been proposed. The mechanism consists of four linear actuated magnets. And the remanent magnetization of the iron ball is utilized. Summary of this paper are as follows.

1. A noncontact rotation control method using remanent magnetization was proposed.
2. A prototype of rotation system was made.
3. Control system for rotation system was made.
4. An experiment examination was carried out and it was succeeded.

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