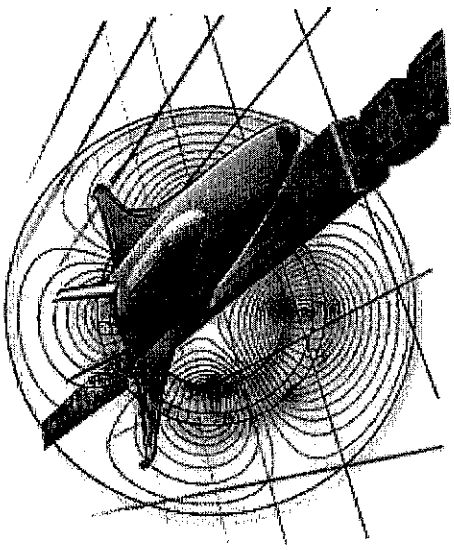
6th International Symposium on Magnetic Suspension Technology



Turin, Italy - Politecnico di Torino
October 7-11, 2001

Micro levitation system with motion contorl

Takeshi Morita*, Koichi Oka[1] and Toshiro Higuchi[2]

Advanced Engineering Center, RIKEN,
2-1 Hirosawa, Wako, Saitama, 351-0198, Japan
(Present) Ceramics Laboratory, Material Department,
Swiss Federal Institute of Technology - EPFL,
CH - 1015 Lausanne, Switzerland,
Phone:+41 21 693 5887: Fax: +41 21 693 5810

[1]Kochi University of Technology, Miyanokuchi 185, Tosayamada-cho, Kochi, 782-8502, Japan

[2]The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8654, Japan

Abstract

A micro levitation system utilizing a permanent magnet attached to a linear actuator is proposed for purposes of micromanipulation. The air gap length between a small iron ball and a permanent magnet is adjusted to balance the magnetic force and gravity force. A piezoelectric actuator is used to control the air gap length because it is simple construction and might be free from heat problems. As a fundamental experiment, a small iron ball 2.0 mm in diameter was successfully levitated. This success should contribute to future studies that utilize electrostatic force or intermolecular force as an attractive force.

Introduction

In the 1980s, micro electrical mechanical systems (MEMS) attracted great attention, with the result that many micromotors and sensors were fabricated and successfully operated [1-3]. In the next stage, smart handling tools would be indispensable in order to assemble these delicate micro parts. Such noncontact manipulation is desirable both because microparts are easily broken, and because contact manipulation produces fine dust that can be harmful to the environment.

Several levitation systems have already been proposed based on the above considerations [4-7]. These systems utilize magnetic coils for generating an attractive force. However, the magnetic coils have complicated constructions, and in the microscale, the driving current can cause heat problems. Furthermore, only ferromagnetic materials can be levitated by these systems. We therefore conclude that magnetic coils are not suitable for use in micromanipulation systems.

In this paper we propose a micromanipulation system that utilizes motion control [8-10]. Rather than controlling the attractive force by means of a magnetic coil, a permanent magnet was attached to a piezoelectric actuator and the air gap length between the permanent magnet and a target object was controlled. Our system was of simple construction, and the piezoelectric actuator rarely caused heat problems.

There are many attractive forces—e.g., electromagnetic force, intermolecular force, and so on—that are inversely proportional to the square of air gap length. Hence our proposed system would be applicable to micromanipulation using various attractive forces, as well as to manipulation of micro parts or cells.

Our final goal was to manipulate small micro parts with 6 degrees-of-freedom. In advance of this goal, in this study we fabricated a micro levitation system with 1 degree-of-freedom. In this system, a permanent magnet was moved by a piezoelectric actuator. The target object was a small iron ball 2.0 mm in diameter. The gap between a small iron ball and a permanent magnet was controlled in order to balance the gravity and magnetic force. After trial and error, we succeeded in levitating a micro object using motion control.

*Contact author: takeshi.morita@epfl.ch

Principle and construction

As a fundamental experiment, a 1 degree-of-freedom levitation system is investigated in this paper. The active control direction was just parallel to the direction of gravity, i.e., the z-direction. A small iron ball was selected as a target object for the levitation experiment. About other directions, namely x and y-directions are passively stable without any control because levitated object has a spherical shaped.

By controlling the gap so as to balance the gravity and the magnetic force, the small iron ball can be levitated. When the gap is smaller than the target gap, the magnetic force surpasses the gravity. The magnetic attractive force will make the gap increasingly smaller. If no controls are taken to prevent it, this will end in the iron ball attaching to the permanent magnet. In this case, the position of the permanent magnet must be controlled to enlarge the gap. On the other hand, when the gap is larger than the target gap, the iron ball might drop due to the force of gravity. In this case, the permanent magnet should be repositioned to shorten the gap.

The experimental system was composed of a small iron ball, a piezoelectric actuator, a permanent magnet and sensors, as shown in Fig. 1. The iron ball had a diameter of 2.0 mm and weighed 32.8 mg. The permanent magnet was an Sm-Co magnet, and was columnar with dimensions of 2.3 mm diameter and 3.0 mm length. In advance of levitation trial, the magnetic force between the magnet and the iron ball was measured by a load cell. The results are shown in Fig. 2. These measurements confirmed that the magnetic force was inversely proportional to the square of the air gap length.

The permanent magnet was attached to the tip

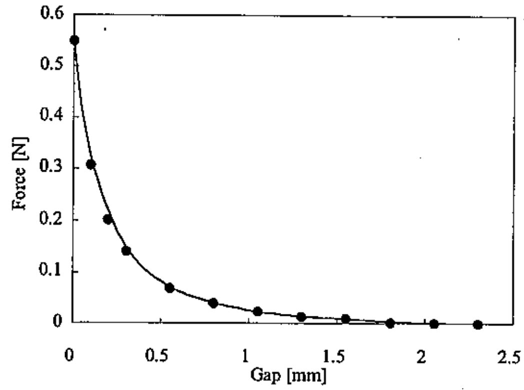


Fig. 2 Relationship between magnetic force and air gap length.

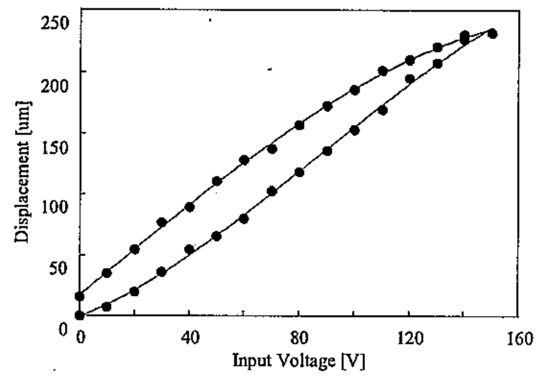


Fig. 3 Relationship between input voltage and obtatined displacement of piezoelectric actuator.

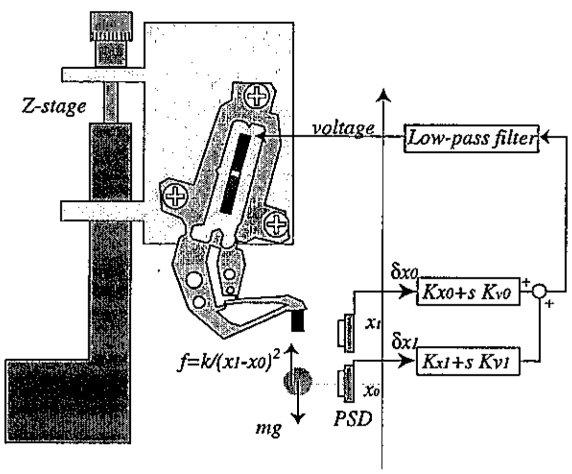


Fig.1 A microlevitation system using motiron control

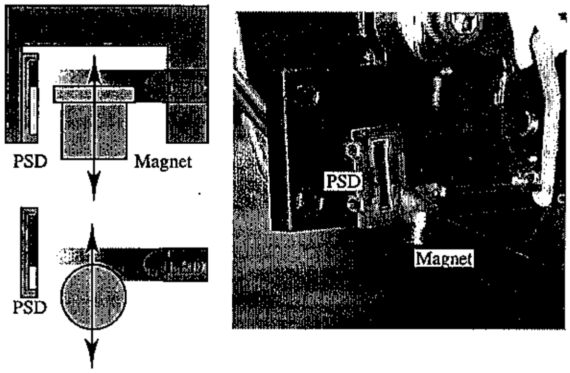


Fig. 4 Principle of position sensor (PSD) for a magnet and a small iron ball. And a photograph of PSD for magnet position sensing.

of the piezoelectric actuator. Generally, the piezoelectric actuator generates giant output force, although the obtained displacement is minute. Even with a layered-type actuator, the maximum displacement is less than 10 μm. Because this value was too small for use with our present levitation system, we used an actuator that realized displacements of 250 μm. This actuator was originally developed by Yano et al. [11] for use in a dot-printer, and contained multi-layered PZT and levers to magnify the displacement. The relationship between displacement and input voltage are shown in Fig. 3. As can be seen, the maximum displacement was about 250 μm at an input voltage of 150 V. Hysteresis is known to be one of the defects of the piezoelectric actuator, and was observed in the present trial. In the control model this hysteresis phenomenon was linearized and neglected.

To control air gap length, it is necessary to monitor the positions of the iron ball and permanent magnet. To detect these positions, a PSD (Position Sensing Device; Hamamatsu Photonics Co., Ltd., Shizuoka, Japan) was utilized. This device can essentially detect the position of a laser spot irradiated on the sensor surface. For the present system, however, we used the device in a different manner. An LED and the PSD were mounted facing each other. The iron ball was placed between the LED and the PSD, and was irradiated by the LED. When the position of the iron ball was changed, both the shadow and irradiated areas changed. The PSD detected the area of irradiated parts, so the displacement of in the z-direction could be measured. In a similar fashion, the position of the permanent magnet was measured with an LED and a PSD. The schematic diagram and a photograph of the PSD for determining the position of the magnet are shown in Fig. 4.

The levitation system was PD control with an analog circuit. The detected positions of the iron ball and permanent magnet were modified with differential modules to obtain the respective velocity values. Then each of the positions and corresponding velocity data were multiplied to feedback gains. Each gain was calculated according to the optimum regulator theory using MatLab software (MA, United States). The multiplied values were added, and the controller outputted its voltage to the piezoelectric actuator. In the actual experiments, the feedback gains were adjusted to achieve a stable levitation. Since the position data from the PSD sensor were noisy, a low pass filter was inserted before the output port. The fundamental resonance frequency of the piezoelectric actuator was 2.3 kHz, and the time constant was more than 10 msec, as will be shown later. Therefore, the cutoff frequency of a low pass filter was selected to be 1.0 kHz.

Model

To analyze the stability of the proposed system, we formulate a numerical model for this system as shown in Fig. 5. The state space model is often used for system analysis or synthesis. This model is useful for multivariable systems, and is usually a linear model. A magnetic force is inversely proportional to the square of the air gap length. It is a nonlinear relationship, and therefore should be linearized to make state space models. The magnetic force F is expressed as

$$F = k\frac{1}{d^2} \qquad (3.1),$$

where k is a constant of the permanent magnet and d is a gap. This relationship can be linearized as

$$\begin{aligned} f(d_{gap}) &= F - m_0 g = \frac{k}{(d_0 + d_{gap})^2} - m_0 g \\ &= \frac{k}{d_0^2}\frac{1}{1+2\frac{d_{gap}}{d_0}+(\frac{d_{gap}}{d_0})^2} - m_0 g \\ &\approx \frac{k}{d_0^2}(1-2\frac{d_{gap}}{d_0}) - m_0 g \\ &= -2\frac{k}{d_0^3}d_{gap} \equiv -k_m d_{gap} \end{aligned} \qquad (3.2).$$

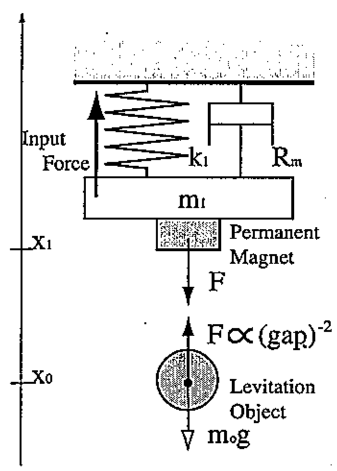


Fig.5 The simulation model for microlevitaion system using motion control. The piezoelectric actuator was expressed with concentrated parameters.

where m_o is the mass of the small ball, d_o is the equilibrium of the gap, d_{gap} is a slight change from the equilibrium gap, and k_m is a proportional constant.

A piezoelectric actuator is constructed with distributed mass and spring. To make a linear model, an equivalent spring k_1, an equivalent mass m_1 and an equivalent damper R_m were measured. By attaching a small mass to the tip of the actuator, the resonance frequency was slightly changed. From this change and the original resonance frequency, the equivalent mass and the equivalent spring could be obtained. The equivalent damper could be calculated with a quality factor and the equivalent spring. The final important parameter was the force factor, which expresses the output force per input voltage. This parameter could be determined with the measurement results of the displacement per unit voltage, as shown above in Fig. 3, and the equivalent spring value. Using the equivalent spring parameter k_1 and the obtained displacement per input voltage ($disp_{piezo}$), the force factor A_{piezo} can be expressed as

$$A_{piezo} = k_1(disp_{piezo}) \qquad (3.3).$$

Using this force factor parameter, the output force, namely control input u is expressed as

$$u = A_{piezo}V \qquad (3.4).$$

The values of measured parameters were

m_o	32.8	[mg]
m_1	174	[mg]
k_m	4.98×10^{-8}	[N/m²]
k_1	26.6	[mN/m]
R_m	1.12	[mNs/m]
d_{piezo}	1.66	[μm/V].

After all, the state space equation is

$$\vec{x} = \begin{pmatrix} x_0 \\ \dot{x}_0 \\ x_1 \\ \dot{x}_1 \end{pmatrix}, \qquad \frac{d\vec{x}}{dt} = A\vec{x} + Bu$$

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ \frac{k_m}{m_0} & 0 & -\frac{k_m}{m_0} & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{k_m}{m_1} & 0 & \frac{k_m - k_1}{m_1} & \frac{R_m}{m_1} \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{m_1} \end{pmatrix} \qquad (3.5)$$

where x_o and x_1 are the position of the small ball and of the permanent magnet, respectively. The optimum feedback gain [k_{x0} k_{v0} k_{x1} k_{v1}] was calculated as [-5400 -1360 790 10.0] using weighting matrix Q=*diag*[1000 100 1000 100] and r=1. In this calculation, sensing parameters [w_{x0} w_{v0} w_{x1} w_{v1}] were [1000[V/m] -3.18[Vs/m] -20300[V/m] 104[Vs/m]].

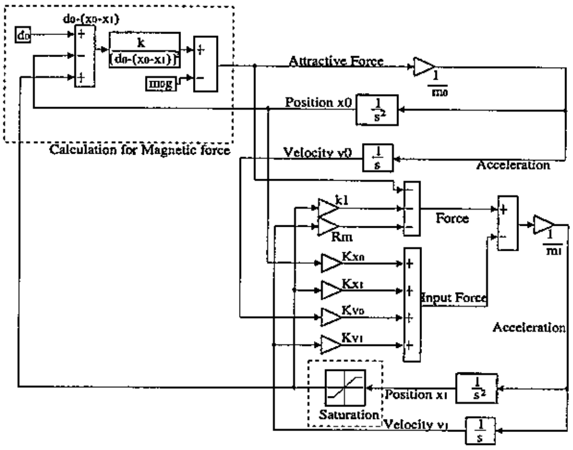


Fig.6 Simulation model for SIMULINK (MatLab). The maximum displacement of piezoelectric actuator and nonlinearity of magnetic force were taken into consideration.

The simulation model is shown in Fig. 6. To obtain the feedback gains, the magnetic force was linearized, although the nonlinear magnetic force was also taken into consideration in this simulation model. Furthermore, a limitation of the actuator displacement was specialized. The results of this simulation model are used for the discussion of experimental results below.

Experiment and resutls

The experiment was carried out as follows. First, the permanent magnet was manually arranged in the upper position by a Z-stage. The sensor for the permanent magnet was also moved by the Z-stage. In this situation, the air gap between the iron ball and permanent magnet was sufficiently large. The gravity surpassed the magnetic force; hence the small iron ball was placed on the base. And the permanent magnet was driven to the lowest position to make the air gap narrow. The maximum displacement of the piezoelectric actuator was 250 μm, so the levitation could not be achieved.

Next, the permanent magnet was very slowly lowered by the Z-stage. When the air gap length became smaller than the target gap, the iron ball was lifted by the magnetic force. Accordingly, the movement of the Z-stage was stopped. The PSD for the iron ball detected the lifting movement, and then the essential control began. The permanent magnet was driven to the uppermost position. Thereafter, the target gap was maintained through control measures.

By monitoring the PSD output signals, it was confirmed that the iron ball was levitated successfully. The feedback gain [k_{x0} k_{v0} k_{x1} k_{v1}] was [-44900 -201 25300 9.6]. The results are shown in Fig. 7. The position of the levitated iron ball was about 40 μm. The PSD sensor, which was used to detect the position of the permanent magnet, was also moved with the Z-stage, so the absolute gap length between the iron ball and the permanent magnet could not be measured. However, it could be verified that the relative gap was kept constant. The time constant was within the range of a few ten milliseconds. For this reason, it was not required that the control cycle be particularly rapid. In this experiment, an analog circuit was used, but in the next experiment of this series, a DSP controller could be used. As shown in Fig. 8, the iron ball remained stable after being raised and reaching the equilibrium position. When the control was started, the vibration of the iron ball and the permanent magnet was observed. This vibration amplitude was rather large, which was attributed to improper feedback gains. In particular, the differential feedback gain of the iron ball k_{v0} was very small compared to the optimum one. The simulation results indicate that if the feedback gain were similar to the optimum one, this vibration would disappear, as shown in Fig. 9. However, when the differential feedback gain was increased in the experiment, the piezoelectric actuator was vibrated with high frequency. This phenomenon may have been due to the noisy signal from the PSD, as observed in Fig. 7 and Fig. 8.

Conclusions

In this paper, a micro levitation system using motion control was proposed. The fabricated system was composed of a permanent magnet, a piezoelectric actuator, a small iron ball and position sensors. The diameter of the iron ball was 2.0 mm and the weight was 32.8 mg. The piezoelectric actuator was of simple construction and was free from heat problems. A state space model was constructed and the feedback gains were calculated by optimum regulator theory.

After trial and error, the small iron ball was successfully levitated. This is the first report to describe a motion control system for micromanipulation. However, a large amplitude vibration was observed. The differential feedback gain used for the iron ball in these experiments was much smaller than the optimum feedback gain. Since the signal-to-noise ratio of the used position sensor was not superior, a larger velocity gain resulted in failure to levitate. For a stable levitation, a superior sensing method will be required.

One of the advantages of the motion control system is that it can be applied to various attractive

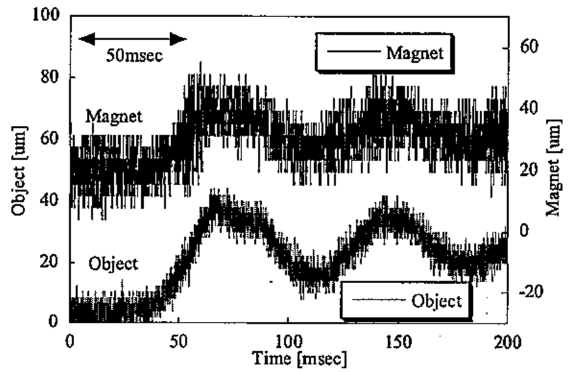


Fig.7 Position of a small iron ball and a permanent magnet. The air gap was controlled to keep constant.

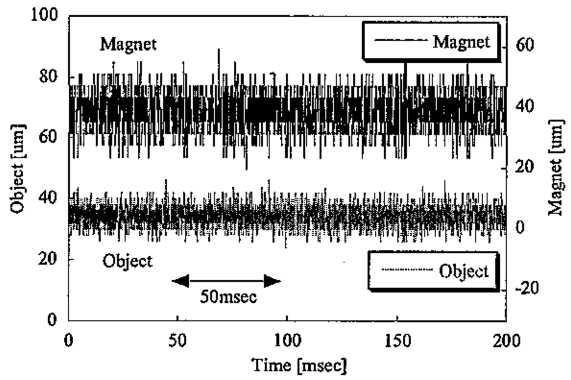


Fig.8 Position of a small iron ball and a permanent magnet during levitation.

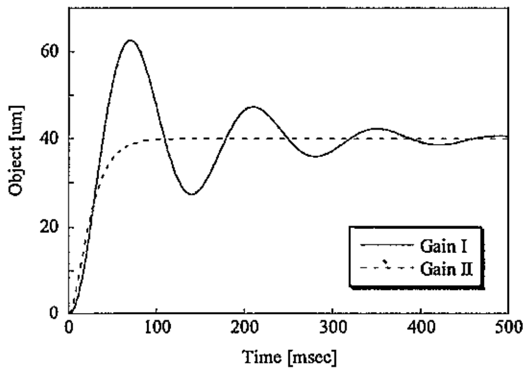


Fig.9 Simulation results with two pairs of feedback gains. Gain I stands for the gains used in experiment and Gain II stands for the optimum feedback gains.

forces, such as electrostatic force or intermolecular force. A smaller system and/or a multi-degrees levitation system will be studied in our next investigations.

Acknowlegements

The authors would like to thank Dr. T. Yano for supplying the piezoelectric actuators and Dr. T. Niino of Tokyo University for useful discussions.

References

[1] L. S. Fan, Y. Tai and R. S. Mullar: IC-processed electrostatic micromotors, *Sensors and Actuators*, vol.20, pp.41-47 (1989).

[2] K. Fukatu, T. Murakoshi and M. Esashi : Electro-statically Levitated Micro Motor for Inertia Measurement System, *Digest of Technical Papers Transducers'99*, pp.158-1561 (1999).

[3] T. Morita, M. K. Kurosawa and T. Higuchi : A Cylindrical Shaped micro ultrasonic motor utilizing PZT thin film, *Sensors and Actuators*, A Physical, vol. 83, pp.225-230 (2000).

[4] R. Y. Siegwart, P. Buhler and D. Baymann : Eddy current beatrings for micro-structure levitation, *Proc. of the 4th Int. Symp. on Magnetic Beatings*, 349 (1994).

[5] Buleuler, Kawakatsu, Tang, Hsieh, Miu, Tai, *Mosesner and Rohner*: Micromachined active magnetic bearings, *Proc. of the 4th Int. Symp. on Magnetic Beatings*, 349 (1994).

[6] R. Muller, H. Bleuler, U. Schlaepfer amd M. Meer: Active micro motor bearings, *Proc. of Fifth International Symposium on Magnetic Bearings*, 401 (1996).

[7] M. Komori and T. Yamane : Development of a Millmeter-sized Active Magnetic Bearing Systems, *Fifth International Symposium on Magnetic Bearings*, pp.405-410 (1996).

[8] K. Oka and T. Higuchi, : Magnetic levitation system by reluctance control", *Int. J. of Applied Electromagnetic in Materials*, 4, pp. 369-375 (1994).

[9] K. Oka and T. Higuchi : A three-degrees-of-freedom maglev system with actuators and permanent magnet, *Trans, IEEJ*, 116-5, pp.138-147 (1996).

[10] K. Oka, T. Higuchi and T. Shimodaira : Hanging Type Mag-lev System with Permanent Magnet Motion Control, *Proc. of the 6th Int. Symp. On Magnetic Bearings* (1998).

[11] Yano, Hamatsuki, Fukui and Sato, *Annual spring meeting of IECE (The Institute of Electronics, Information and Communication Engineers) 1-157*, (1984) (in Japanese).