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Design and Implementation of a 5-DOF Magnetic Levitated Platform

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ABSTRACT

A general purpose magnetic levitated platform (MLP) is designed and implemented in this paper. The specifications of the designed MLP include five degrees of freedom control with a normal shift displacement of 10 mm and normal rotation of 2.1 degrees. Within this range, the proposed MLP can be operated in precision position control with high stability. Non-mechanical-contact position and velocity sensors are implemented to control 6 electromagnets in order to offer levitation forces applied onto the embedded permanent magnets in the platform. The MLP is capable of isolating external vibration and eliminating interference from any sources. Both isolation and tracking effects have been tested, and the results are presented in this paper for the proposed magnetic levitated platform.

Key Words: magnetic suspension and balance system, vibration isolation, 5-DOF control, eddy current sensor

I. Introduction

Magnetic suspension and balance systems (MSBS) are mainly designed for non-friction rotation and/or transportation applications in industry. Many useful applications, either in small-gap systems (Kanemitsu and Watanabe, 1993; Neff and Britcher, 1993), such as magnetic suspension bearings, or large-gap systems (Lin and Lee, 1989; Shirazee and Basak, 1995), such as a magnetic suspension wind tunnel, magnetic levitated train, and large-angle space-based gambling system, have been studied and developed in this decade. In large-gap systems, such as wind tunnels, position measurement technology can be adopted using non-contact devices. Most studies have used optical sensing technology to detect the positions of controlled objects. It is advantageous to avoid electric and/or magnetic interference from vicinity systems. In many small-gap systems, such as bearing or vibration isolators, optical sensing is not easily adopted due to space limitations. Proximity sensors are mostly used to acquire position data as information which can be fed back to controllers and actuators (Yasuda and Ikeda, 1992; Groom, 1989). In such applications, large damping effects of suspended elements are found (Neff and Britcher, 1993). It is not clear how the motion damping corresponding to energy consumption can be defined. In mechanical vibration systems, both position and velocity data are required to obtain the necessary damping force by means of differentiation (Watanabe and Kanemitsu, 1993; Yasuda and Ikeda, 1992). However, noise interference is a serious concern in such applications because it devalues the damping effect. Appropriate use of motion sensors is important and can provide a good damping effect under minimum power dissipation.

For the 1-DOF vibration problem, the actuator is usually chosen by simple attractive system such that its output can obtain better body-rigid and damping effects. Such a simple attractive system may result in an unstable open loop. An additional controller is required to stabilize the system. A magnetic suspension system is difficult to use in closed-loop applications because of its low damping effect. This reduces the reliability of the magnetic suspension system. Such a system can not sustain a large impact force if its stability level is not high enough. This makes sensor position determination and controller design very important for overall system performance. Normally, a suspension system uses position sensors for position signal feedback. Due to high frequency switching interference in the actuator, the controller may not obtain good closed-loop damping. Instability and unreliability may result from any impact force since the energy can not be eliminated instantly.

In the design process for an MLP, the levitation force generated from the interaction between the electromagnet and permanent magnets can be formulated (Neff and Britcher, 1993) first. Then the sensors can be determined based on system performance requirements. In this paper, an eddy current type distance sensor is used to meet the system characteristics of an MLP. The output of the eddy current sensor is proportional to the flux variations. Unlike other sensors, it can also provide a combination of displacement and velocity. In the eddy current sensor, the velocity feedback provides proper damping for a good tracking effect. Under impact force tests, the electromagnet could generate a large relative damping force, which could minimize the impact effect. To promote the fast response characteristics of the MLP, an analog control circuit has been designed and fabricated.

II. System Description

1. System Structure

The structure of the proposed magnetic levitated platform (MLP), as shown in Fig. 1, includes 6 actuators and 6 sensors, which are used to achieve 5 degrees of freedom operation. Four actuators are located on the top of the platform to control the vertical displacement and two rotating angles while two actuators are located at the side of the platform to control the horizontal displacement. To reduce the amount of unnecessary payload on the table, the table was carefully considered. The prototype platform is 32 cm × 32 cm, and is composed of non-metal materials weighing 1240 grams. A design which combines a sensor and an actuator is shown in Fig. 2. The embedded permanent magnets are magnetized with 5000 Gauss; they are 25 mm diameter × 25 mm length and are located at the four corners of the platform. The magnets are used in the actuators to increase the levitation force and in the eddy current sensors to induce the velocity changes. The levitation force is generated by electromagnets with 7600 turns of 0.8 mm coils on an annealed iron core. The electromagnetic flux density can be 1100 Gauss under a 0.8 Ampere excitation current. Under loading conditions, the maximum distance from the actuator to the permanent magnet on the movable part of the MLP is within 52 mm. Considering possible load variations, the operation point is chosen such that there is a distance of 35 mm between the actuator and the permanent magnet. This distance has been confirmed by experiments in fabricating the sensor coil and its permanent magnet with a 30 to 40 mm range to obtain appropriate velocity feedback. To avoid magnetic flux interference among the actuators and sensors, they are located 95 mm apart from each other. In the design considerations, the dimensions of the MLP were determined by considering the space limits of our laboratory as well as other parameters.

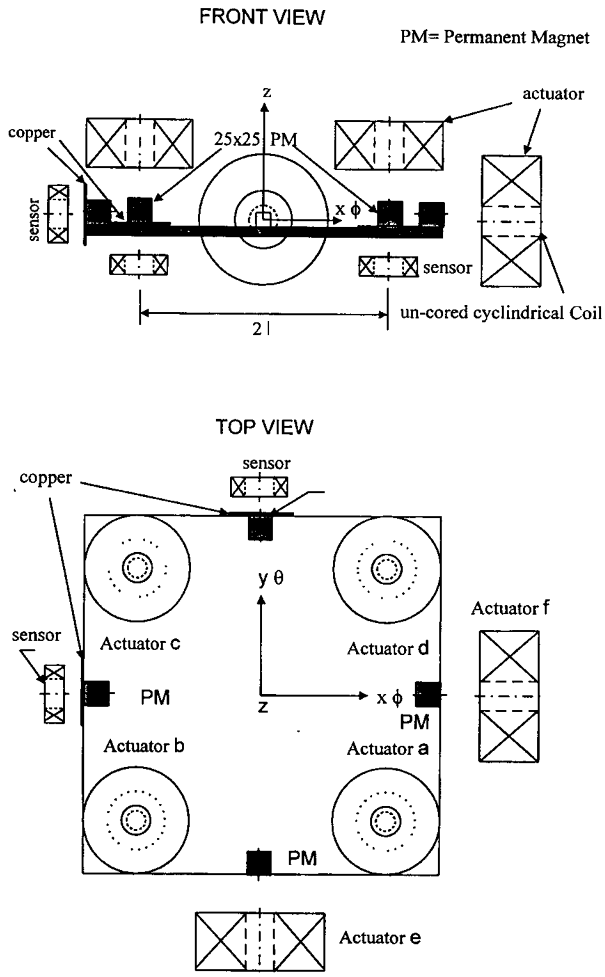

Fig. 1. MLP system structure.

2. Static Measurement of Magnetic Force

The flux distribution on the permanent magnets is not homogeneous along the axis and surface. For the permanent magnets, the central flux density is as high as 5000 Gauss while the flux at the edges drops to only 3000 Gauss. The same flux distribution is observed in an electromagnet. Therefore, the interaction force on both the permanent magnet and electromagnets is affected by the flux distribution pattern. A general method is used to measure the interacting forces between the electromagnet and permanent magnet, and to then establish a force model by means of curve fitting (Neff and Britcher, 1993). The applied force F on the permanent magnet and the electromagnet contains two force components: one is the acting force from the

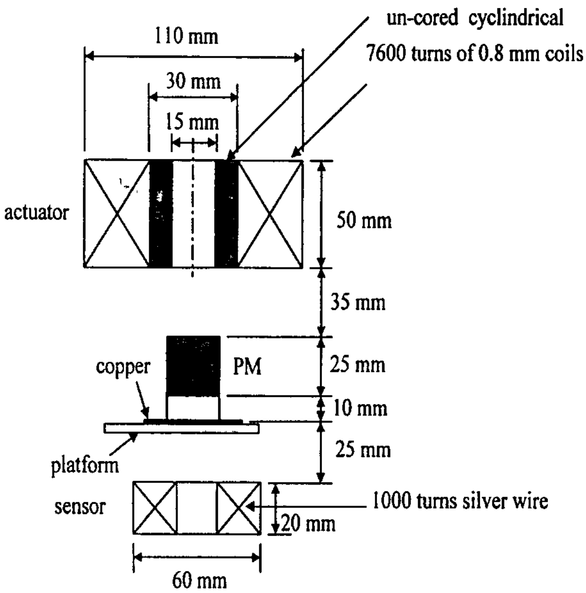

Fig. 2. Sensor and actuator mechanic structure.

electromagnetic coil to the permanent magnet, F_1, and the other is the attraction force from the permanent magnet to the iron core, F_2. From the electromagnetic field measurement as shown in Fig. 3, the acting force F_1 is proportional to the coil current. An assumption can be made as follows:

$$F(D,I)=F_1(D,I)+F_2(D)$$

$$=\frac{I}{(c_1+c_2\times D^2)}+\frac{D}{(c_3+c_4\times D^2+c_5\times D^4)}\ . \quad \textbf{(1)}$$

First, let the actuator current I=0, and use the curve fitting method to find force F_2, induced by the permanent magnet between the permanent magnet and the electromagnet. Figure 4 shows the resultant magnetic force induced by the permanent magnet:

$$F_2=\frac{100D}{-1-3D^2+4D^4}\ . \quad \textbf{(2)}$$

From a series of tests and measurements, the force model of the active suspension system can be identified and expressed as:

$$F(D,I)=F_1(D,I)+F_2(D)$$

$$=\frac{100I}{1+1.1D^2}+\frac{100D}{-1-3D^2+4D^4}\ , \quad \textbf{(3)}$$

where F is the applied force (Newtons), I is the electromagnetic coil current (Ampere), and D is the separation distance between the electromagnet and the permanent magnet (cm). Figure 5 shows the resultant magnetic force in relationship to the coil currents of the electromagnetic actuator and its separation distance from the permanent magnet. By means of linearization, the force variation around the operation point can be formulated as:

$$F(D\ ,I)=F(D_0,I_0)+\frac{100}{1+1.1D_0^2}(I-I_0)+[\frac{-220I_0D_0}{(1+1.1D_0^2)^2}$$

$$+\frac{100(-1+3D_0^2-12D_0^4)}{(-1-3D_0^2+4D_0^4)^2}](D-D_0)+\ldots, \quad \textbf{(4)}$$

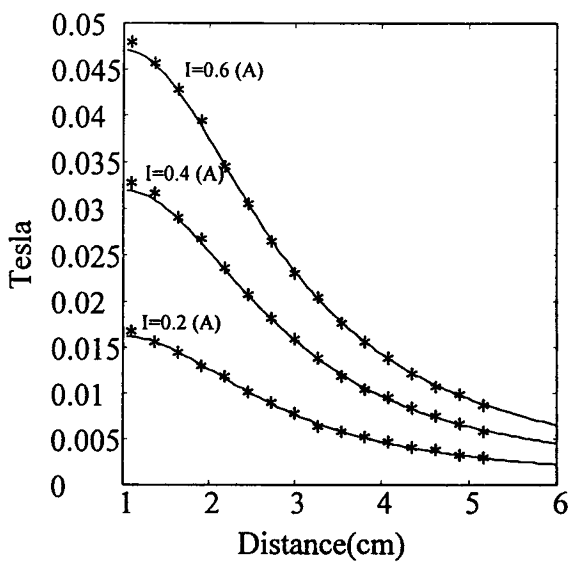

Fig. 3. Summary of the fitting curves of the magnetic field.

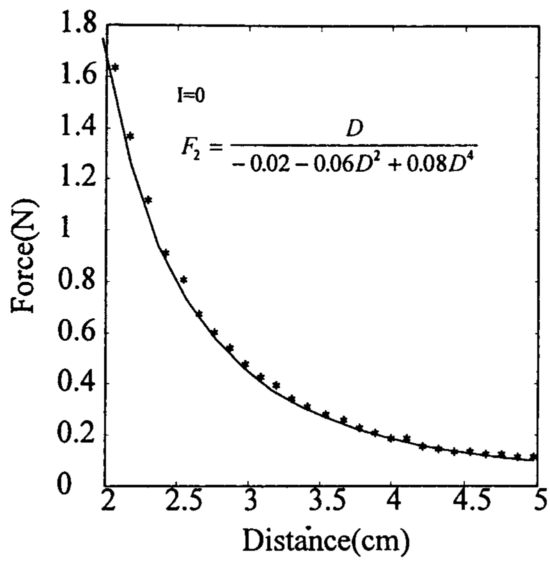

Fig. 4. Force induced by the permanent magnet.

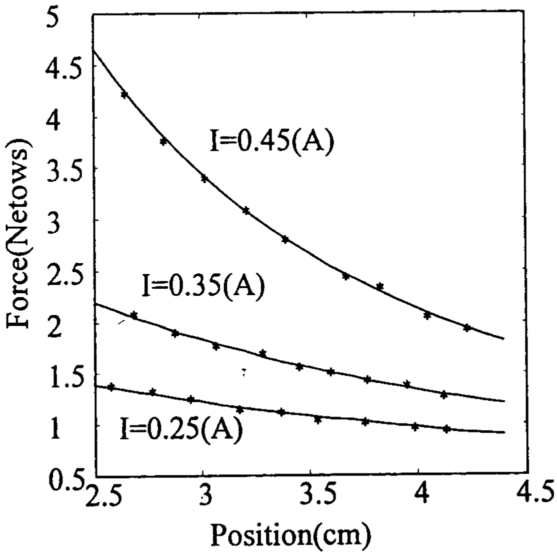

Fig. 5. Force between the magnet and the electromagnet.

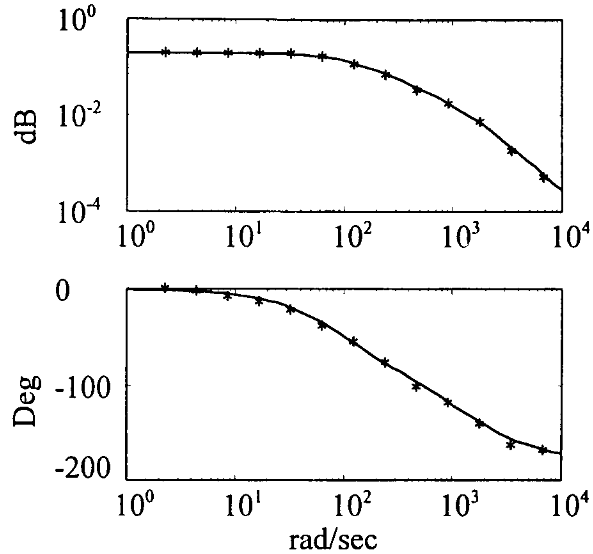

Fig. 6. Frequency response of the magnetic coil connected to the power supply.

where $F(D_0, I_0)$ is the magnetic force caused by the EM coil current I_0, and the controlled PM is located at an equilibrium point D_0.

3. Dynamic Characteristic of the Magnetic Coil

After the force model is established, the frequency analyzer is used to examine the spectrum of the power supply connected to the magnetic coil between the input voltage and the output coil current. The frequency response is shown in Fig. 6, where it can be found that the dominant pole is located at 1400 rad/sec and has a 0.015 sec time delay. The dominant pole is far away from the imagery axis and can be canceled, and a pole is added to approach the time delay of 0.015 sec:

$$\frac{I(s)}{E(s)} = \frac{0.2}{\frac{s}{1400}+1} e^{0.015s} \approx \frac{0.2}{0.015s+1} . \tag{5}$$

4. Sensors

The eddy current distance sensor used in this paper is shown in Fig. 2. It is very simple but stable, adjustable with measurement gain, and free from optical interference. However, due to the limited sensing range, the eddy current distance sensor is accurate only for small gap applications. When the MLP is operating in a larger range, the control gain from the system position feedback is generally limited to avoid output saturation. Under such a limitation, the control system is easily disturbed by noise when the MLP is operating in a small range and the system loses good stability. The solution is to increase the velocity feedback in the loop to overcome the operating range limit and obtain good stability performance.

Figure 7 shows the sensor circuit of the proposed MLP. The sensor circuit is an LC oscillator circuit used to generate a sine wave with an oscillation frequency determined by the L and C. In this design, the sensor is an inductor L of a 1000 turn coil, as shown in Fig. 2. A back induced voltage is detected due to flux variations from the permanent magnet. This results in a variation of the output voltage on the operation amplifier (OPA). The amplitude of the OPA output voltage indicates the changes of the position and

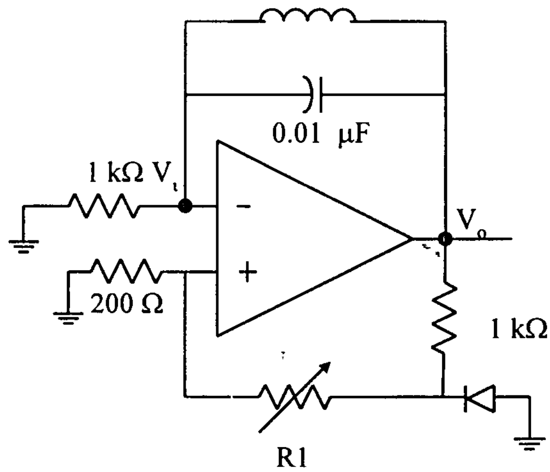

Fig. 7. Eddy current sensor circuit.

velocity. The variation flux in the sensor L indicates three different effects:

(1) The oscillation of sensor L changes the flux and causes the suspended copper sheet to generate an eddy current, thereby resisting flux changes. The flux change resulting from the eddy current reflects back to the inductor coil and causes the OPA output voltage to change. From experiments, the suspended platform, joined together with the copper sheet, moves 20 mm, resulting in a 4 Gauss change of the electromagnetic field. This flux change, from real time measurement, offers position change information for the suspended platform.

(2) The permanent magnets on the platform cause a flux change due to position variation and induce a voltage change across the sensor L. The flux change on the sensor L has a close relationship with the position of the permanent magnet on the platform and its velocity of movement. By adjusting the arrangement of the permanent magnets, the velocity feedback can be tuned and sensed.

(3) Theoretically, the flux variation also causes the flux change on the electromagnetic coils. However, compared to the former two effects, this has only a very small effect on the sensor L which can be ignored.

Figure 8 shows different sensor gain resistances (R1 value) in relation to the measured OPA output voltage and the platform gap distance of the MLP.

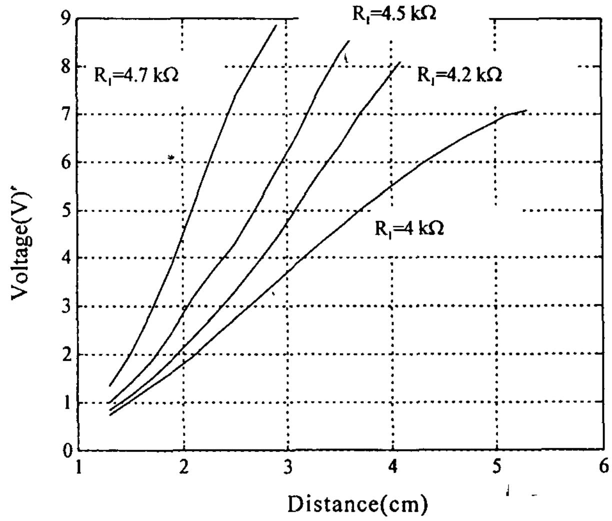

Fig. 8. The relationship of the measured output voltage with the MLP distance with different R1 values.

III. Controller Design

1. Pole Placement

In the control problem of the proposed MLP, appropriate gap selection for the distance from the sensor coil to the permanent magnet can lead to proper velocity feedback and a better damping effect in system control. A PD controller is used for MLP control. However, this system also requires a tracking effect to monitor dynamic performance during vibration and impact. The trade-off between the PD gains may be important to obtain both the tracking and damping effects. In the sensor design, the velocity feedback is closely related to the gap distance between the electromagnetic coil and the permanent magnet on the platform.

In the system structure design, the gap distance from the permanent magnet to the sensor coil was found to be 30 to 40 mm and that from the eddy current metal to the sensor coil was found to be 20 to 30 mm, as shown in Fig. 2. From the experiments, the sensor gain resistance R1 was selected to be 4.5 K Ohms, as indicated in Fig. 8. Under this condition, the velocity feedback gain was selected to be 0.112. The load on the platform was 310 grams, and the gap distance from the permanent magnet to the actuator was maintained at 35 mm in the experiments. From Eq. (3), we can obtain the operating current, which is 0.349 A. Substituting the separation distance and current data (35 mm and 0.349 A) into Eq. 4, we can obtain the position feedback gain A, which is 1.17, and the current feedforward gain B, which is 6.9. Based on the pole placement method (Franklin and Powell, 1986), we chose roots at -159 and $-25\pm18j$; then, the proportional amplifier gain was selected to be 1.18, and the differential amplifier gain was selected to be 0.041. The linearized feedback control scheme of the MLP is shown in Fig. 9.

2. Effect of Sensor Zero

To understand the effect of the sensor zero on system performance, we chose a phase-lead controller from the PD-controller for the magnetic suspension system and compared the root locus of the feedback zeros using the eddy current sensor and position sensor.

The block diagram in Fig. 9 can be simplified as the unit feedback block diagram shown in Fig. 10. The conventional position sensor can not measure and identify the system velocity, say K_v=0. The zeros of the PD controller have to be chosen to be at the left hand side (K_d/K_p=0.035) of the plant poles for stable control. The root locus will appear to be similar to that shown in Fig. 11. Since a closed-loop system can not shift its zeros away from the imaginary axis, it is

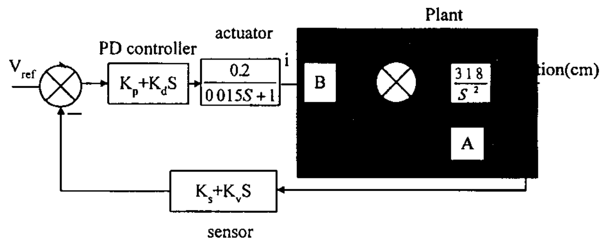

Fig. 9. Block diagram of the linearized feedback control scheme.

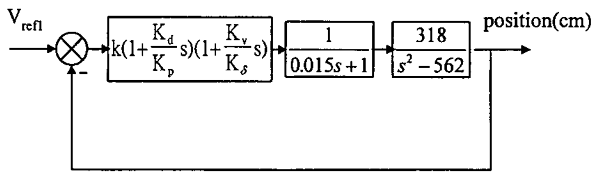

Fig. 10. Standard unit feedback configuration.

clearly seen that the conventional position sensor has poor stiffness and damping characteristics. However, since the eddy current sensor can detect the velocity signal, the open loop transfer function has one additional zero. When the gain is limited in practice, the controller zero and the sensor zero(K_v/K_δ=0.035, K_d/K_p=0.035) can be allocated at the right hand side of the actuator pole; then, the root locus becomes similar to that shown in Fig. 12. Following the increase of the gain, the closed loop zero is apparently shifted leftward. This implies that the magnetic suspension system has been greatly improved with better stiffness and damping characteristics. The control result tends to be a stable condition.

IV. Implementation and Results

From the design and implementation, the proposed magnetic levitated platform (MLP) could sustain an additional 600 gram weight with 4 mm displacement at the equilibrium position. To test the performance of the MLP, both vertical and edge impact forces were applied. Figure 13 shows the steady state performance of the MLP under normal test conditions at a step response. The response time was fast, and the micro meter accuracy of the MLP performance could be examined.

Figure 14 shows the impulse responses of the MLP. The impact experiments were carried out using a 250 gram free-falling body from 10 cm, 20 cm, and 30 cm heights dropped onto the platform. The instantaneous increase of the velocity feedback returned the MLP to very stable conditions although the estimated impact force on the MLP could be 3 times larger. This showed good performance of the eddy current sensor and indicated a very good damping effect.

Figure 15 shows the angular responses of 250 gram free-falling body impact on the edge of the MLP from 3 cm, 5 cm, 10 cm heights. Figure 16 shows the horizontal responses of lateral impact forces of 0.1 N, 0.2 N, and 0.3 N. From these results, the response time required to reach stable conditions could be controlled to within 0.5 seconds. The performance in terms of the impact responses of the proposed MLP appeared to satisfy the desired specifications.

For the edge impact, since the edge sensors fed

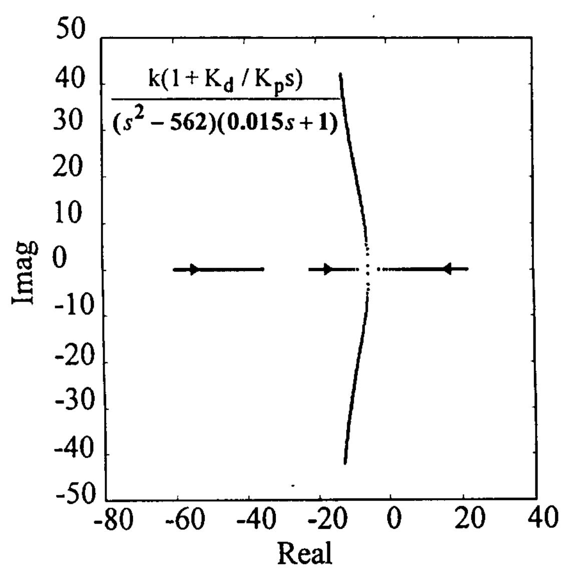

Fig. 11. Root locus without sensor velocity feedback.

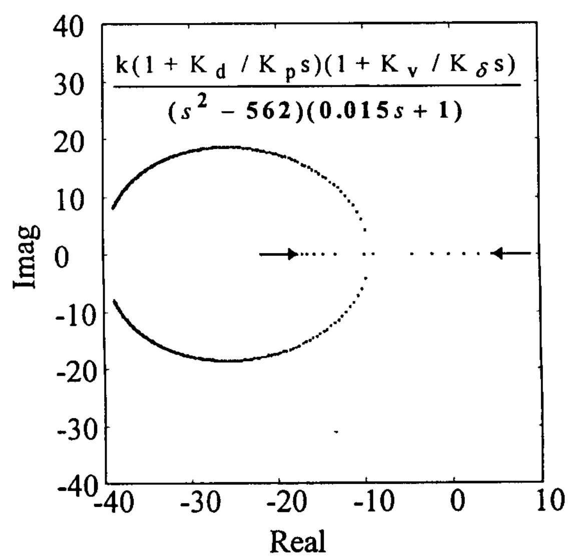

Fig. 12. Root locus with sensor velocity feedback.

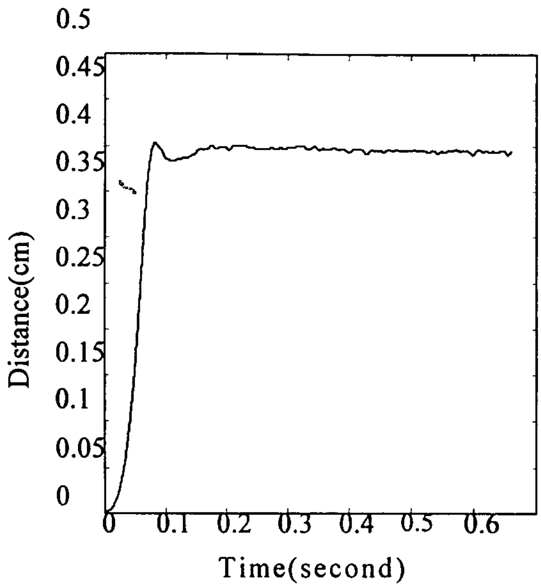

Fig. 13. Step response and stead-state performance of the MLP.

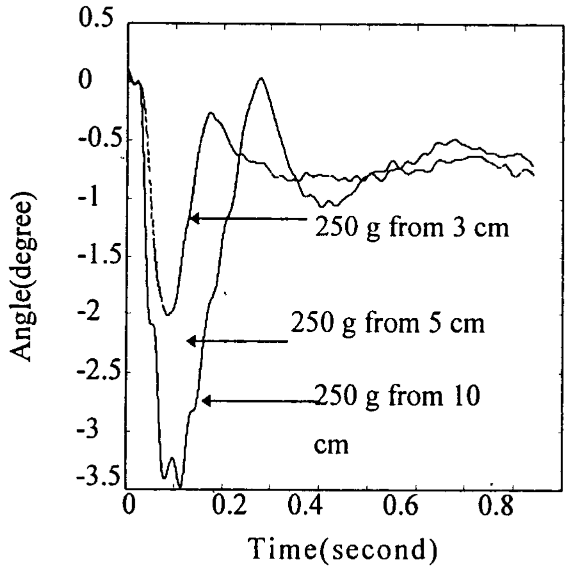

Fig. 15. Rotational changes due to edge impacts.

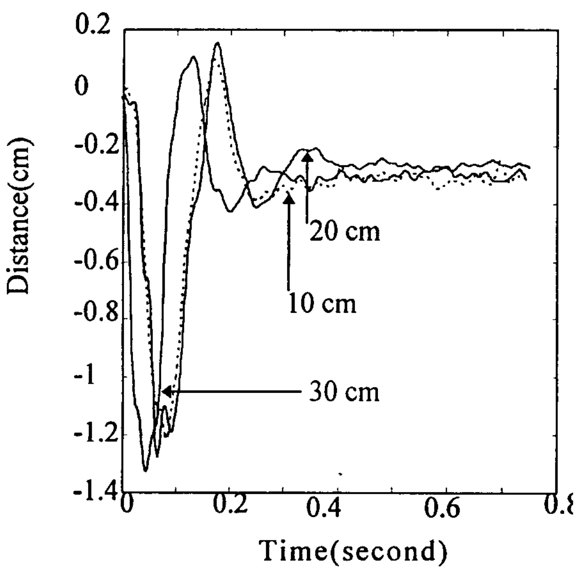

Fig. 14. Central position changes due to vertical impacts

both distance and velocity information back to the controller, a heavier impact force resulted in a larger distance change. This occurred because the platform was a rigid body; when a corner received a force displacement, the result was a reverse displacement at the other corners. This phenomenon was suppressed in the vertical impact from the four corners. Comparing Figs. 14-16, this effect indicates that a balanced response of the MLP could be expected while the unbalanced response could still be controlled. However, the response speed was fast.

From another point of view, the proposed magnetic levitated platform should maintain a certain tracking capability for a wider variety of applications. The tracking performance was tested in the experiments. When the MLP had a horizontal movement, the horizontal actuators (e,f) should have overcome the horizontal acting force from the vertical actuators (a,b,c,d). An observable lag in horizontal tracking resulted. Figure 17 shows vertical and horizontal tracking effects of the proposed MLP, where the solid line is the tracking results comparing to the dashed reference line. It is obvious that the vertical

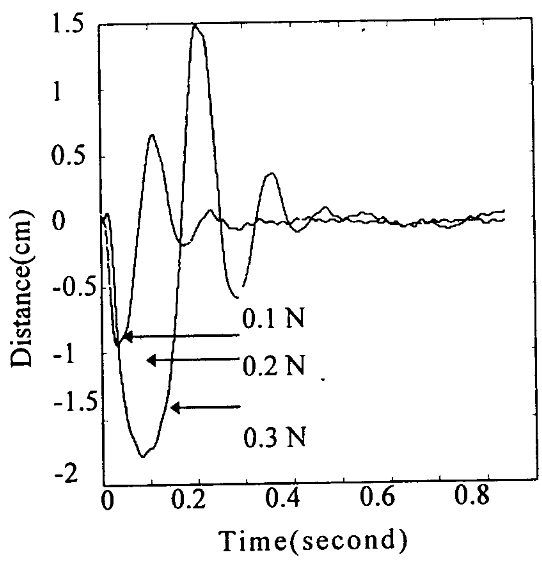

Fig. 16. Horizontal position changes due to horizontal impacts.

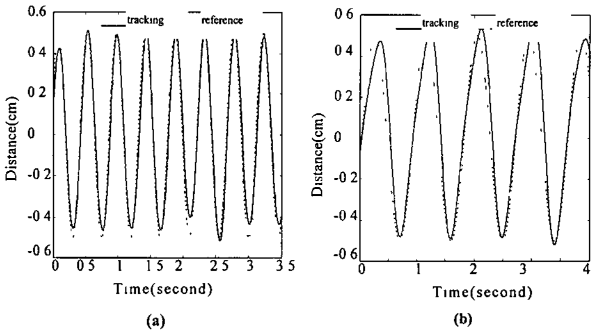

Fig. 17. (a) Vertical position tracking effect of the MLP. (b) Horizontal position tracking effect of the MLP.

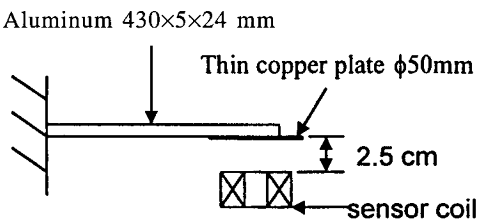

Fig. 18. Eddy current sensor test set-up.

position tracking effect was much better that the horizontal position tracking effect. Using the MLP, good vertical tracking performance could be obtained.

V. Conclusion

In this paper, a five-degree-of-freedom magnetic levitated platform (MLP) has been designed and implemented. This system uses the eddy current sensor to feed back both position changes and velocity changes into the control loop. The sensor itself is simple and reliable with minimum tuning effort required to obtain good performance. Compared to previously developed methods, the sensor and actuator designs are valuable for the proposed magnetic levitated platform applications. As a result of proper use of the eddy current sensors, the overall performance of the designed MLP demonstrates its ability to isolate vibration and impact from external interference. Although the control loop uses only a PD control, the control results are still remarkable. With respect to power dissipation, the power demand of the proposed MLP is quite small when strong permanent magnets are used in combination with sensors and actuators as shown in Fig. 2. Its structure design is recommended for further researches. Based on the test results, the proposed magnetic levitated table may become a useful structure for practical applications.

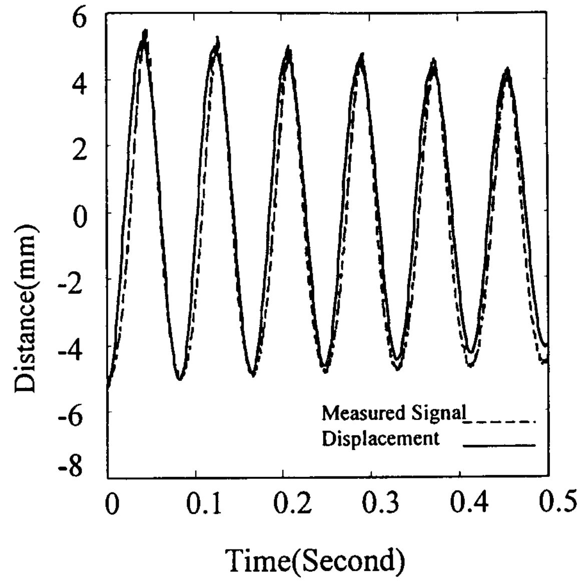

Fig. 19. Tracking effect of the eddy current sensor.

Appendix: Un-modeled Eddy Current Sensor

As shown in Fig. 18, an aluminum stick was fixed at one end with the other end free. If we lifted this aluminum stick to obtain a 5 mm displacement and then let it go freely, a small oscillation of about 12 Hz could be observed. This oscillation was detected from the eddy current sensor as shown in Fig. 19 to obtain a result. This result indicated a very good tracking effect. The eddy current sensor was, therefore, used as a zero-order instrument. It was not necessary to identify the dynamic response of the eddy current sensor in such an application.

Nomenclature

I	Coil current (A)
D	Deflection (cm)
F	Force (N)
K_d	Differential amplifier gain
K_p	Proportional amplifier gain
K_v	Sensor velocity gain
K_δ	Sensor deflection gain
A	position feedback gain
B	current feedforward gain

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五自由度磁浮平台之設計與應用

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摘　要

本篇文章討論磁浮平台的設計與實現。此一平台具有五個自由度、上下及水平位移1 cm、與旋轉角度2.1°的懸浮能力，此平台有精密的位置控制與高穩定度的效果。此系統的特色爲懸浮平台與地板間無機械的接觸，完全依賴六個電磁鐵提供所需的懸浮力量，與其對應的感測器量測其相對位置，並在平台上置有對應的強力磁鐵來增強平台懸浮的能力。磁浮平台主要目的爲隔絕外在的震動對平台所產生的干擾。本實驗所使用的感測器爲結合距離與速度的感測輸出，其優點爲追蹤效果以及衝擊抑制的效果均較佳。