11th International Symposium on Magnetic Bearings
August 26-29, Nara, Japan

ZERO POWER CONTROL FOR PERMANENT MAGNETIC SUSPENSION SYSTEM

Feng Sun
Dept. of Intelligent Mechanical System Eng., Kochi University of Technology,
Kami, Kochi, 782-8502, Japan
118003b@gs.kochi-tech.ac.jp
Koichi Oka
Dept. of Intelligent Mechanical System Eng., Kochi University of Technology,
Kami, Kochi, 782-8502, Japan
Oka.koichi@kochi-tech.ac.jp

ABSTRACT
This paper describes a permanent magnetic suspension system that consists mainly of a permanent magnet, an actuator and sensors. This magnetic suspension system is based on a zero power control method, which results in almost no power consumption in the equilibrium state. A spring is installed in the magnetic suspension device to counterbalance the force of the actuator on the mass gravitation in the equilibrium position. An integral feedback loop is used in the controller to achieve zero actuator current when the device is in a balance state. A model was set up for feasibility analysis, a prototype was manufactured for experimental confirmation, numerical simulations for the zero power control were carried out based on the model, and experiments were completed for practice confirmation using the prototype. Some results of simulations and experiments are shown and analyzed here, and conclusions based on these results are given.

INTRODUCTION

Conveyance vehicles have been in increasing demand because of the need for an ultra-clean environment in many fields, such as semiconductor processing, biotechnology experiments and material processing. The mechanisms and tools used in these fields must be ultra-clean so as not to contaminate samples. Moving frictional parts in direct contact, such as reduction gears, bearings, wheels and rails, are the main sources of dust and particles, which cannot be avoided. This paper sets out to demonstrate that this magnetic levitation mechanism can be used to realize noncontact conveyance mechanisms.

In active magnetic suspension field, there are main three kinds of magnetic levitation systems, which are electromagnetic suspension systems, permanent magnetic suspension systems and hybrid electromagnetic suspension systems including a permanent magnet and an electromagnet. The advantages of permanent magnetic suspension systems are no heat generation and no requirement for a coil. A permanent mag-lev system that controls the attractive force through varying the air gap distance has been proposed by the authors [1]. The system's characteristics are the nonuse of an electromagnet and the utilizations of a permanent magnet and a linear actuator. However when this type of magnetic levitation system suspends with noncontact, the actuator has to support the mostly weight of the whole device including itself. Therefore, the energy consumption becomes a significant problem. In order to solve this problem, a zero power control method is adopted to reduce the energy consumption. A spring is assembled in the device and an integral feedback loop is used in the control system, and then almost no energy is consumed in the suspending state.

First, the principle of the permanent magnetic suspension is explained. Second, a magnetic suspension system prototype is presented and a model is analyzed. Third, a zero power controller is indicated. Last, some results of numerical simulations and experiments used the prototype are shown, and these results indicate that the zero power control makes the levitation system almost consume no energy in the suspending state.

PRINCIPLE OF MAGNETIC SUSPENSION

The principle of this levitation system is explained in terms of the suspension system scheme shown in Figure 1. The suspension system consists of a permanent magnet, an actuator and a mass. The permanent magnet

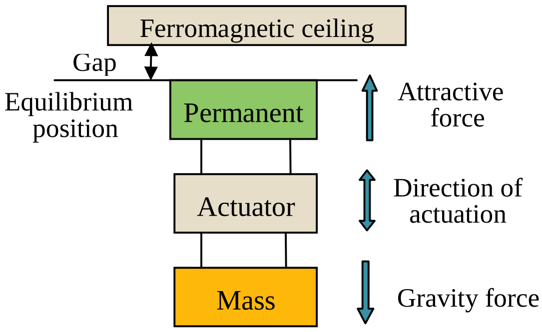

FIGURE 1: A suspension system scheme

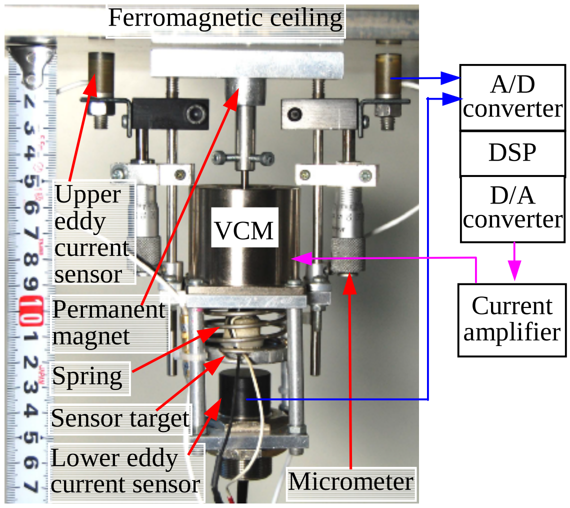

FIGURE 2: Photograph of suspending mag-lev system

generates the suspension force; the actuator performs the suspension control; and the ferromagnetic ceiling acts as a track. The suspension device is hung from the ferromagnetic ceiling by the attractive force of the permanent magnet. When the suspension device is levitating, the levitation direction is vertical, and the magnet's attractive force is equal to the gravitational force on the suspension device in the equilibrium position [1-5]. Then, based on the principle that the magnetic force is inversely proportional to the square of the gap between the magnet and the ferromagnetic ceiling [6], the actuator controls the distance between the magnet and the mass so as to adjust the gap. When the gap is larger than the balance gap, the actuator increases its distance in response to the magnet's motion from the equilibrium position towards the ceiling; when the gap is smaller than the balance gap, the actuator decreases its distance in response to the magnet's motion away from the ceiling. In this way, the suspension mechanism is able to levitate stably without contact.

PROTOTYPE OF MAG-LEV SYSTEM

A prototype photograph of a permanent magnetic suspension device is in Figure 2. The prototype mainly consists of a permanent magnet, a voice coil motor (VCM), a spring, three eddy current displacement sensors and a frame. The whole device that weighs 746.8 grams has two parts: the magnet part including a permanent magnet, a slider of VCM and a sensor target; the frame part including the VCM stator, the three sensors and the frame, which are the remainders of the prototype except the magnet part. The weight of the magnet part is 79.5 grams and the frame part is 667.3 grams.

The VCM (voice coil motor) used in this mag-lev prototype is a linear actuator powered by Lorentz force. The VCM's important characteristics are fast response, high-frequency vibration capability, zero nonlinear friction and a direct drive mechanism, which are indispensable for levitating an object steadily without contact. The VCM used here has a driving length of 15 (mm) and a maximum generating force of 10 (N) at a coil current of 2 (A). This VCM has two parts: a stator consisting mainly of a permanent magnet and an iron coil, belonging to the frame part; and a slider in the form of a coil, belonging to the magnet part. The VCM is the only active driving element that is utilized to control the device suspension stably at equilibrium.

A spring is installed between the frame part and the magnet part of the device. When the VCM current is zero, the spring generates a force to counterbalance the gravitational force acting on the frame part at the balance position. This is the primary requirement for zero power control.

Three eddy current displacement sensors are installed in the prototype. The upper two measure the frame part position comparing with the ferromagnetic ceiling. These two sensors have a resolution of 0.5 (μm) and a measurement rang of 4 (mm). They are installed on the stays of the frame, and the positions can be adjusted precisely by two micrometers along the stays. Moreover, these two sensors were arranged at two sides of the permanent magnet symmetrically for co-location. Hence the frame part position is determined by the average of these two sensors' signals. Additionally, the lower sensor measures the relative position of the magnet part to the frame part. It has a resolution of 5 (μm) and a measurement range of 10 (mm).

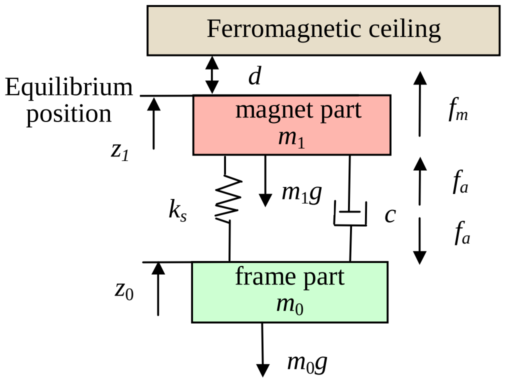

FIGURE 3: Model of suspension system

The controller of this suspension system is a DSP controller, shown in Figure 2. Signals from three sensors are input to the DSP controller through 12-bit A/D converters. Based on these signals, appropriate current values are computed by the controller. The current values are converted to analog current by D/A converters, and then amplified by a current amplifier. The final actual current controls the VCM to maintain the system suspension stably.

A model of the levitation system as shown in Figure 3 has been set up for feasibility studies, stability confirmations, numerical simulations and feedback gains calculations. According to the model, the motion equations of the frame part and the magnet part are indicated as

$$m_0\ddot{z}_0 = k_s(z_1 - z_0) + c(\dot{z}_1 - \dot{z}_0) - f_a - m_0 g \qquad (1)$$

$$m_1\ddot{z}_1 = k_s(z_0 - z_1) + c(\dot{z}_0 - \dot{z}_1) + f_a + f_m - m_1 g \qquad (2)$$

In the equations, m_0, m_1 are the mass of the frame part and the magnet part; z_0, z_1 whose positive directions are the upper, are the displacements of the frame part and the magnet part; f_a is the generating force of VCM; f_m is the attractive force of the permanent magnet; k_s is the spring constant; and c is the damping coefficient including spring fading characteristics, VCM bearings frictions, and air viscosities.

Additionally, the relationship between the input current and the VCM generating force is represented by the equation as

$$f_a = k_t i \qquad (3)$$

Where, k_t is the VCM propulsive coefficient, and i is the

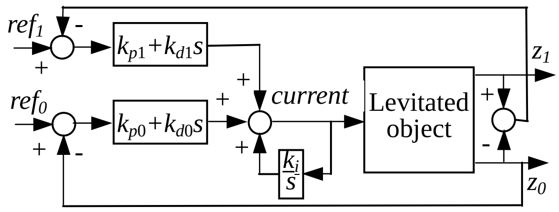

FIGURE 4: Block diagram of control system

VCM input current.

The relationship between the permanent magnet attractive force and the air gap distance is shown in the equation as

$$f_m = \frac{k_m}{d^2} \qquad (4)$$

Where, k_m is the coefficient of magnetic attractive forces, and d is the air gap distance between the ferromagnetic ceiling and the permanent magnet.

ANALYSIS OF ZERO POWER CONTROL

When this permanent mag-lev system is suspended, the attractive force of permanent magnet has to equal the gravitational force of the whole mag-lev mechanism. And the frame part weight is transmitted to the magnet through the actuator. That is means, when maintaining the device suspending, the actuator has to drive the whole frame part simultaneously. Thus, the actuator requires a greater current, and vast energy consumption is produced.

As we known, there is a similar problem in electromagnetic suspension system (EMS system). The current of electromagnetic coil is great, and generates a lot of heat. Therefore vast energy is consumed. For solving this problem, a hybrid electromagnetic suspension system that includes a permanent magnet and an electromagnet has been developed. When the device suspending, the permanent magnet force counterbalances the gravity of the object, and the electromagnetic force maintains the balance. Consequently, energy is saved. This is the zero power control of the EMS system.

A controller used for the axial bearing in the pediaflow ventricular assist device, consists of a standard linear-quadratic (LQ) regulator and a Kalman filter. The Kalman filter estimates the equilibrium position, where the LQ regulator drives the system reach. The actuator force settles to zero. This estimated controller is a virtual zero power (VZP) controller [7].

However, in this kind of mag-lev system with a linear actuator and a permanent magnet, a different method is adopted and a similar purpose is attained. For reducing energy consumption, a spring is installed between the frame part and the magnet part as shown in Figure 2. The resultant force of the spring force and the VCM force transmits the interactional force of the magnet part and the frame part. In the equilibrium state, when the gravity of the frame part equals the spring force, the VCM force is only used for stabilizing levitation. Consequently, the energy is saved.

Additionally, there are many ways to realize zero power control in the mag-lev system controller, such as using an observer, a current integral feedback, an object weight estimation. In this paper, a current integral feedback method is investigated.

As shown in Figure 4, the block diagram is the controller of the permanent mag-lev system, having an integral current feedback loop for zero power control. There are two large PD feedback loops. The lower PD feedback loop compares the frame part with the ceiling. The upper PD feedback loop is related to the relative displacements between the magnet part and frame part. Both PD feedback loops calculate the current values based on the sensors' signals in order to make the VCM maintain the system levitation robustly. When the mag-lev system is suspended, no external input is imported, and the system simply maintains itself, suspended stably in an equilibrium position. To some degree, this suspension system is an autonomous system, and the control system is an adaptive control system. The requirements of the control system are quick response and reliable stability. Moreover the equilibrium positions are not fixed. When the load varies, the equilibrium position changes. When the controller was designed, all above-mentioned factors were considered. Therefore the proportional controller and differential controller were adopted and the integral controller was not used in both feedback loops.

Besides the two large PD feedback loops, a local current integral feedback loop is used before the levitated object block to implement zero power control. When current flows through the VCM circuit, this integral feedback loop reduces the current. The current reduction affects the distance between the frame part and the magnet part, and the resulting distance variation causes the spring length and the generating force to change. Finally, when the spring force becomes equal to the frame part weight, the VCM current reaches zero. Nevertheless the load is not varying, so the gap between the permanent magnet and the ceiling never changes. Furthermore, the k_i value for the gain of the integral current feedback loop influences the speed of current variation. If the value is large, the current reaches zero quickly. However, that works against system stability. Rapid current variation will result in system instability. Therefore, a proper k_i value is very important for system stability.

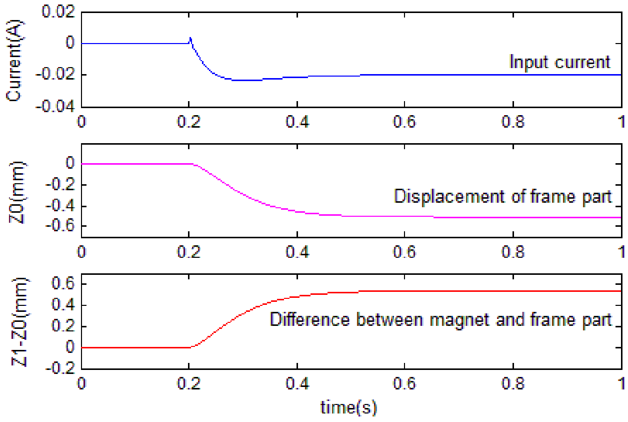

FIGURE 5: Simulation results without springs and without zero power control

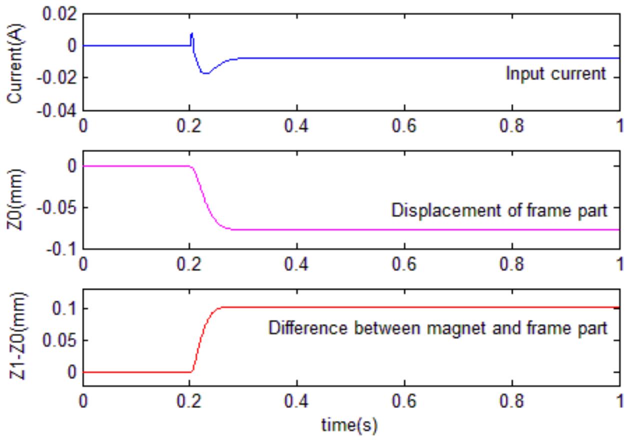

FIGURE 6: Simulation results with springs and without zero power control
spring constant k_s =0.6N/mm

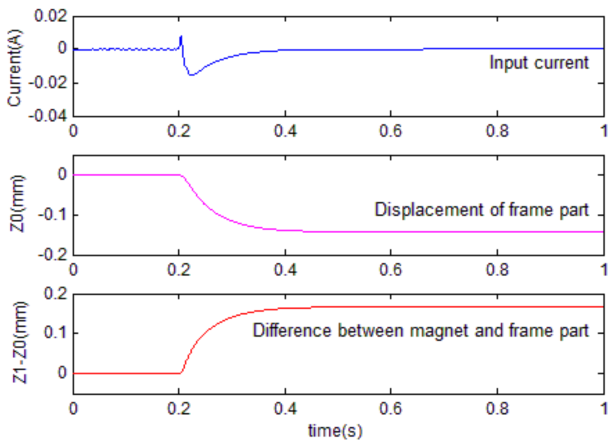

FIGURE 7: Simulation results with springs and with zero power control
spring constant k_s =0.6N/mm

RESULTS OF NUMERICAL SIMULATION AND EXPERIMENT

For feasibility study, numerical simulations carried out with the nonlinearity of the attractive force. The simulations are examined respectively for some typical conditions, such as the mag-lev system without springs and without zero power control, with springs and without zero power control, with springs and with zero power control, and using different springs and different k_i gains.

In this paper, the simulation results of just three kinds of conditions indicate respectively in Figure 5, Figure 6 and Figure 7. When a 10 grams weight was added to the system as a step during levitating, the VCM current, the frame part displacements and the relative displacements between the magnet part and the frame part were recorded. The step was added at 0.2 second, and the responses were recorded until 1 second. The varieties of the current and the displacements were plotted in Figures, as the upward direction is positive.

The results of the simulation without springs and without zero power control are in Figure 5. The upper graph shows the VCM current response, the middle one indicates the frame part displacement, and the lower one shows the relative displacement between the magnet part and the frame part. When weight is added, the original balance state is broken, because the gravitational force is then greater than the attractive force of the magnet. Therefore, the frame part displacement shown in the middle graph decreases. In order to make the system return to balance, the actuator must reduce the gap between the magnet and the ceiling, and then the attractive force will increase until it is equal to gravity. In this process, the magnet part ascends, and the VCM increases the distance between the magnet part and the frame part, requiring much larger current than before, as shown in the middle and lower graphs of Figure 5. Thereafter, the suspension system reaches the balance state again. However, the VCM current is approximately -0.02 (A) greater than in the original equilibrium state, because all additional loads are supported by the VCM.

The results of the simulation with springs and without zero power control are in Figure 6. In this simulation, the used spring constant is 0.6 (N/mm). All results are similar to the outcomes in the simulation without spring and without zero power control at the beginning of the control process. However, in the steady state in Figure 6, the current value is approximate -0.01 (A), which is smaller than in Figure 5. The reason is the resultant force of the spring force and the actuator force sustains the additional loads.

The results of the simulation with springs and with zero power control are in Figure 7. In this figure, the spring constant and all the feedback gains are same to Figure 6, except for the gain of the current integral feedback loop, because there is no integral feedback loop in the simulation of Figure 6. The gain is 35 in the simulation of Figure 7. The comparison between Figure 6 and Figure 7 suggests that, even though the same gains was used in these two simulations, the time of reaching balance state is different, and the time in Figure 7 is longer than in Figure 6. However, the VCM input current converges to zero in the stable state in Figure 7. That means, in this simulation with spring and with zero power control, the VCM consumes no energy, and the spring force counterbalances all gravities in the equilibrium state.

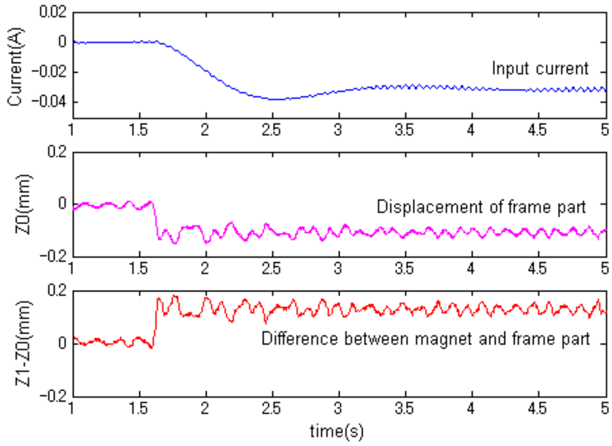

FIGURE 8: Experiment results without springs and without zero power control

All numerical simulation results imply that zero power control used a spring and an integral current feedback loop is feasible in this permanent magnet suspending system.

Furthermore, the noncontact suspension experiments were implemented with the prototype shown in Figure 2 that was a photograph of the successful suspending prototype. Many kinds of experiments were completed corresponding to numerical simulations in the same conditions and feedback gains. Some experimental results indicate in Figure 8 to Figure 12 in different conditions. In these results, the responses of the suspension system were investigated with a step disturbance of adding 10 grams weight to the device. The weight put on the levitating device at the time between 1.5 seconds and 2 seconds, and the responses were recorded from 1 second to 5 seconds. All the current results in figures were passed through the low pass filters.

The results of the experiment without springs and without zero power control are in Figure 8. This figure is corresponding to Figure 5. The same feedback gains and same conditions are used. From the results, when

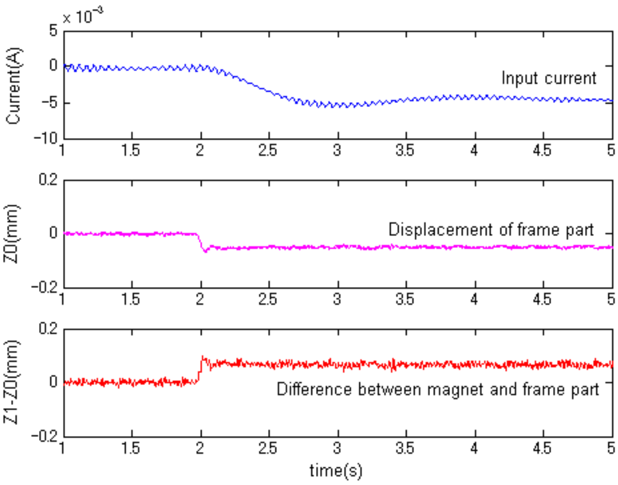

FIGURE 9: Experiment results with springs and without zero power control

spring constant k_s =0.6N/mm

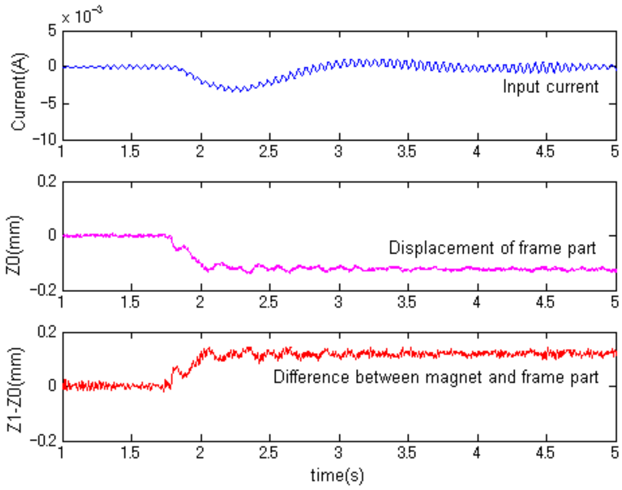

FIGURE 10: Experiment results with springs and with zero power control

spring constant k_s =0.6N/mm

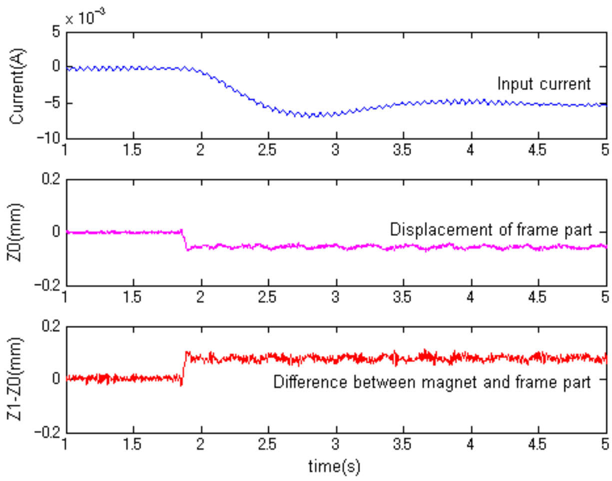

FIGURE 11: Experiment results with springs and without zero power control

spring constant k_s =0.7N/mm

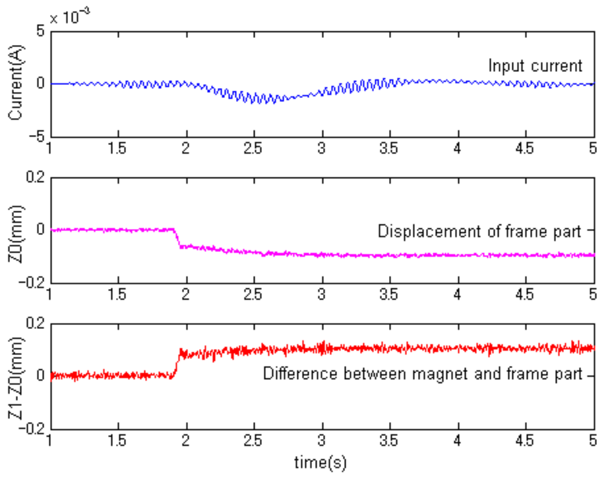

FIGURE 12: Experiment results with springs and with zero power control

spring constant k_s =0.7N/mm

the mag-lev system is suspending stably, the device is not resting at the equilibrium position, but it is vibrating around the equilibrium position. After adding the weight and reaching the balance state, the input current is more than -0.02 (A) because of the additional weight.

The Figure 9 and Figure 10 are the results of the experiment with the same feedback gains and conditions to the simulation results of Figure 6 and Figure 7. From the current graph in Figure 9, after putting on the weight, the current value is just approximate –0.005 (A) in the stable state. It is much smaller than the current in Figure 8. The reason about that is the resultant force of the VCM and the spring was supporting the additional weight. However in Figure 10, the current is converging to zero, and the variation values of the displacement of frame part and the difference between magnet and frame part are greater than them in Figure 9. The current integral feedback loop arouses all variations between in Figure 9 and in Figure 10. The integral loop decreases the VCM input current converging to zero, and then the VCM generates no force, so all gravities are maintaining by the spring. Therefore, the spring length becomes short, and the changing length equals the value of the difference between the magnet and frame part, even equals the changing length when 10 grams weight is putting on the spring directly. However, the integral loop is not able to affect the air gap between the magnet and the ceiling, so the declining displacement of the frame part is larger than in Figure 9.

Moreover, the experiments using different springs and different k_i gains were investigated too. The results are in Figure 11 and Figure 12. The experiment of Figure 11 carried out with the same feedback gains and same conditions of Figure 9 except the spring. The spring constant is 0.7 (N/mm) in Figure 11. The differences of the experiments between Figure 12 and Figure 10 were the spring constant and the gain of the current integral feedback loop. The gain in the experiment of Figure 10 was 35, but it was 25 in Figure 12. Because different springs require different gains, and stronger springs require smaller gains. Comparing Figure 11 and Figure 12 with Figure 9 and Figure 10, there is a little difference. The displacements are becoming a little smaller, because a stronger spring has a smaller variation length for same weight.

In conclusion, all experiments results suggest that the zero power control is successful for this kind of permanent mag-lev system.

CONCLUSIONS

Based on theoretical model analyses, realistic prototype confirmations, numerical simulation results for numerous different feedback gains and all kinds of conditions, and practical experiment data with the same feedback gains and conditions as in the simulations, the following conclusions can be suggested.

Firstly, through using a digital controller with two PD feedback loops, the suspension system with the permanent magnet and the linear actuator can be levitated stably with no contact.

Secondly, the zero power control method using a spring in suspension device and a current integral feedback loop in the controller can reduce energy consumption considerably in this permanent mag-lev system.

Finally, it is possible to realize contactless, low energy consumption transportation using this permanent mag-lev system and zero power control.

REFERENCES

1. K. Oka, T. Higuchi and T. Shiraishi, Hanging Type Mag-lev System with Permanent Magnet Motion Control, Electrical Engineering in Japan, Vol.133, No.3, pp.63-70, November 2000

2. K. Oka, Noncontact Manipulation with Permanent Magnet Motion Control, Proceeding of the 4th International Symposium on Linear Drivers for Industry Applications, LDIA2003, pp.259-262, September 8-10, 2003, Birmingham, UK

3. Cui Tianshi, Fujiwara Yusuke and Oka Koichi, 2 DOF Maglev System with Permanent Magnet Motion Control, SICE Annual Conference 2005 in Okayama, August 8-10, 2005 Okayama University, Japan, pp.3859-3862

4. K. Oka and Tianshi Cui, 2 DOF Suspension Mechanism for Noncontact Manipulation with Permanent Magnet Motion Control, Proc. of Mechatronics and Robotics 2004, 383-387(2004)

5. Koichi Oka, Fujiwara Yusuke, Cui Tianshi and Li Chen, Noncontact Spinning Mechanism Using Linearly Actuated Magnets, Proc. of the 5th International Symposium on Linear Drivers for Industry Applications, LDIA2005, September 25-28, 2005, Awaji Yumabutai, Hyogo, Japan, pp.552-555

6. Ehsan Shameli, Mir Behrad Khamesee and Jan Paul Huissoon, Nonlinear Controller Design for a Magnetic Levitation Device, Microsyst Techno (2007), 13:831-83

7. Myounggyu D. Noh, James F. Antaki, Michael Ricci, Jeff Gardiner, Dave Paden, et al, Magnetic Design for the PediaFlow Ventricular Assist Device, Artificial Organs (2007), 32(2):127-135