Semi-Zero Power Control of a Permanent Magnetic Suspension System with Constant Air Gap Length

Feng SUN # 1*
Shenyang University of Technology
Shenyang, China

Koichi OKA #2
Kochi University of Technology
Kochi, Japan

Junjie JIN #3
Shenyang University of Technology
Shenyang, China

Tao HONG #4
Shenyang University of Technology
Shenyang, China

Yingyuan LU #5
Shenyang University of Technology
Shenyang, China

Abstract

This paper proposes a semi-zero power control method of a permanent magnetic suspension system using a flux path control mechanism with a constant air gap. This permanent magnetic suspension system consists of a disk-type permanent magnet, two “F” type iron cores, a rotary actuator with an encoder and a reducer, and a suspended object with a bar shape. In this system, the gravitational force of the suspended object is transmitted to the base part of the system, and the actuator only drives the permanent magnet rotate. Therefore, this system can realize the semi-zero power control. Moreover, when the mass of suspended object increases, the system just changes the bias angle of the permanent magnet, and maintains the air gap length constant. In another way, this system also can maintain the bias angle of magnet constant, and changes the air gap length short to realize the semi-zero power control. This paper focuses on the semi-zero power suspension characteristics of this system, elaborates the system’s mechanism, and analyzes the semi-zero power suspension performances with a constant air gap length.

1 Introduction

Save-energy is a constant topic for industry. Magnetic suspension is a new supporting technology in industry. How to save energy in magnetic suspension systems becomes a focus for many researchers in magnetic suspension field.

In electromagnetic suspension system, Morishita and Azukizawa have proposed a zero power control method using the hybrid electromagnet with the aim of reducing steady state energy consumption [1]. Myounggyu et al. have proposed a virtual zero-power controller consisting of a standard linear-quadratic (LQ) regulator and a Kalman filter [2]. In permanent magnetic suspension system, Mizuno et al. have proposed a zero power magnetic suspension system with a permanent magnet and three flux-path control modules [3]. Ueno and Higuchi presented a zero-power magnetic levitation technique using a composite of magnetostrictive and piezoelectric materials [4]. Moreover, we have proposed a zero power control method using a spring and an integral current feedback loop in a hanging type magnetic suspension system [5].

Until now, all save energy strategies in magnetic suspension systems realize the zero power control in stable state by reducing the air gap when the load increases. However, the reducing air gap will decrease the suspension safeness. In order to solve this problem, we have proposed a magnetic suspension system, which has some advantages, such as zero suspension force, variable magnetic poles, and semi-zero power suspension with a variable air gap way and a constant air gap way [6]. And this paper will focus on the semi-zero power suspension characteristics of this system, elaborates the system’s mechanism, and analyses the semi-zero power suspension performances with the variable air gap way and the constant air gap way. The analysis will be done in mechanism, in theory, and will be examined by simulation and experiment.

*Contact Author Information: sunfeng@sut.edu.cn, Address: No.111, Shenliao West Road, Economic & Technological Development Zone, Shenyang, 110870, P.R.CHINA, Phone Number: +86-18904040100

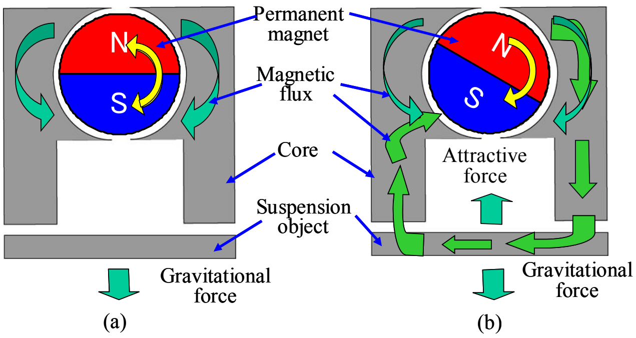

Figure 1: Principle of variable flux path control

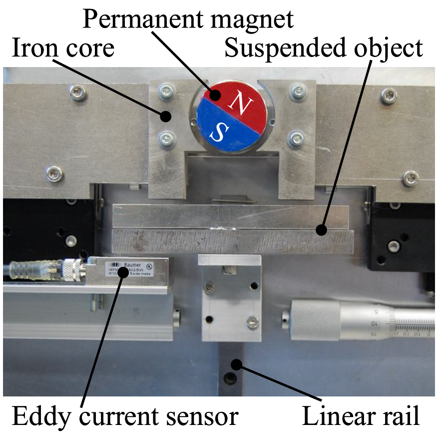

Figure 2: Photograph of the experimental mechanism

2 Principle of Variable Flux Path Control Mechanism

The principle of variable flux path control mechanism can be understood from Figure 1. This figure shows a schematic diagram of a disk permanent magnet, two opposite F-type iron cores and a suspended object. In order to understand easily, we assume that: (I) The magnet has an N pole of half part and an S pole of opposite half part as shown in Figure 1; (II) There is no flux leakage to the air in this magnetic suspension system. Figure 1 (a) shows that the magnetic poles of the magnet are aligned in the vertical direction and the N pole is at the upper side and the S pole is in the lower side. In this case, the facing angle of the N pole and S pole to each core are same, so all magnetic flux comes from the N pole and is absorbed into the S pole through each core respectively. There is no flux flowing through the suspension object, so zero attractive force generates between the cores and the levitated object. However, Figure 1 (b) shows the magnet rotated a certain angle, the facing angle of the N pole becomes bigger than the S pole in the right core, and that is reverse in the left core. Since that, the flux from the N pole in the right core is more than that in the left core. Some of the flux in the right core flow through the suspension object to the left core and is absorbed by the S pole. Consequently, there are some flux flowing through the levitated object, and the attractive force is generated. The flux flowing through the levitated object becomes more as the rotated angle is larger, until the rotated angle reaches 90 degrees. After 180 degrees, the direction of the flux flowing through the levitated object is reversed. The magnetic suspension system changed the magnetic poles of the stator cores.

3 Experimental Mechanism

3.1 Experimental Mechanism

An experimental mechanism of the proposed magnetic suspension system was constructed, and the photograph of the prototype is shown in Figure 2. This prototype consists mainly of a disk-type permanent magnet, a rotary actuator containing a gear reducer and an encoder, a pair of opposite F-type permalloy cores, a suspended object and an eddy current sensor. The magnet that is located in the opposite F-type cores is a neodymium magnet and magnetized in radial direction. The diameter of the magnet is 30 mm and the thickness is 10 mm. A rotary actuator behind of the magnet drives the magnet rotate. The actuator that has an encoder measuring the angle of the magnet cannot be seen in Figure 2. The thickness of the two cores is 10 mm that is same as the magnet. The suspended object is installing on a linear rail, and can move in the vertical direction only. The position of the levitated object is measured by an eddy current sensor, of which the measurement range is from 2 mm to 3 mm and the repeat accuracy is 10 µm.

3.2 Semi-zero Power Control in Mechanism

According to the principle of the variable flux path control and the experimental mechanism, we can see that, the attractive force for suspension is generated by the magnetic flux flowing through the air gap between the iron core and the suspension object, and the magnetic flux is generated by the permanent magnet, which is driven by the rotary actuator. The gravitational force of the suspension object is handed over to the base through the iron core, and the actuator just drives the permanent magnet rotate, does not support the gravitational force of the suspension object. Therefore, the magnet in mechanism will maintain a state of rest in the stable suspension state, the consumption power of the actuator should be zero in principle.

However, in order to examine the effect of the magnetic potential to the permanent magnet, the rotational

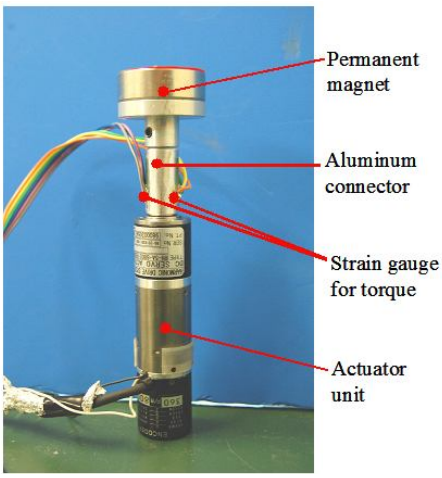

Figure 3: Measurement device for rotational torque of magnet

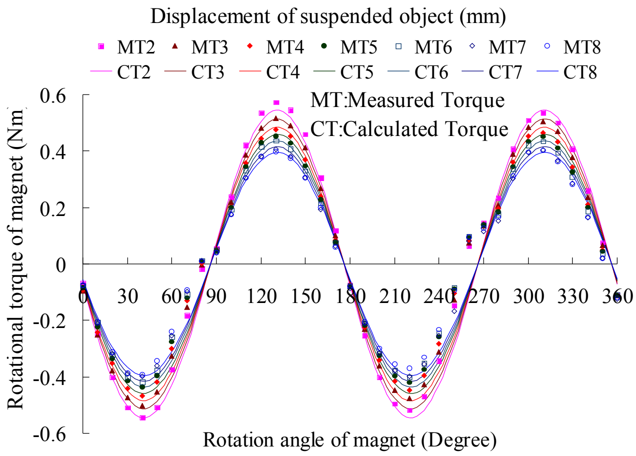

Figure 4: Rotational torque of permanent magnet

torque of magnet was measured with strain gauges, when varied the rotational angle of the permanent magnet and the air gap between iron cores and the suspended object. Two pieces of strain gauges for measuring torques were pasted on the side of the connector between the rotary motor and the permanent magnet, and the rotational torque was measured. In the measurement experiment, the permanent magnet was rotated at 10 degrees as one step in one revolution, and the air gap length between the cores and the suspended object was increased at 1 mm as one step. The rotational torque of magnet was measured when the air gap length varied from 2 mm to 8 mm. The measurement device is shown in Figure 3. The measured results of the rotational torque are shown in Figure 4. The results indicate that the rotational torque is similar to a sine curve of two times of rotational angle, and decreases with increasing the air gap. These results also reveal that the state torque of the magnet are related with both the rotational angle of magnet and the air gap between the iron core and the suspension object. However, basing on the structure of mechanism, we can deduce that the consumption power of the actuator will be nonzero, but the value will be small in the stable suspension state. As a result, this magnetic suspension system can realized a semi-zero power suspension state.

4 Semi-Zero Power Control Analysis

4.1 Analysis in Mathematical Model

Basing on the mechanism and some basic experiments, the mathematical model was built as following [6].

$$J\ddot{\theta} = c_1\dot{\theta} + k_\tau \frac{\sin 2\theta}{d + \Delta d_\tau - z} + k_t i \tag{1}$$

$$m\ddot{z} = c_2\dot{z} + k_m \frac{\sin^2\theta}{\left(d + \Delta d_f - z\right)^2} - mg \tag{2}$$

Where, J is the moment of inertia of motor and magnet; θ is the rotational angle of magnet; k_τ and Δd_τ are the constants of rotational torque of magnet; d is the initial air gap length; z is the displacement of suspension object; k_t is the torque constant of motor; i is the current of motor; k_m is the constant of suspension force between the iron core and suspension object; m is the mass of the suspended object; c_1 and c_2 are the damping coefficients of the motor and the suspended object, respectively.

According to this mathematical model, when the suspension object is suspended in a static state, the differential terms become zero, i.e., the acceleration terms and the damping force become zero. From Equation (2), we can see that, when the mass m increases, the rotational angle and air gap length can be changed to pursue the equilibrium state, we can change one parameter and maintain the other one as a constant. Therefore, we can obtain the constant air gap length suspension or the constant rotational angle suspension. Moreover, in Equation (1), both the rotational angle and the air gap length are relation to the current of motor, but we cannot know whether the current value is small or not just according to the equations.

Parameter	Value	Parameter	Value
d_0 (mm)	0.9	k_t (Nm/A)	0.69
Δd_f (mm)	1	k_m (Nm^2)	1.06×10^{-4}
Δd_τ (mm)	12	k_τ (Nm^2)	-8.726×10^{-3}
θ_0 (degree)	40	g (m/s^2)	9.8

Table 1: Parameters using in simulation

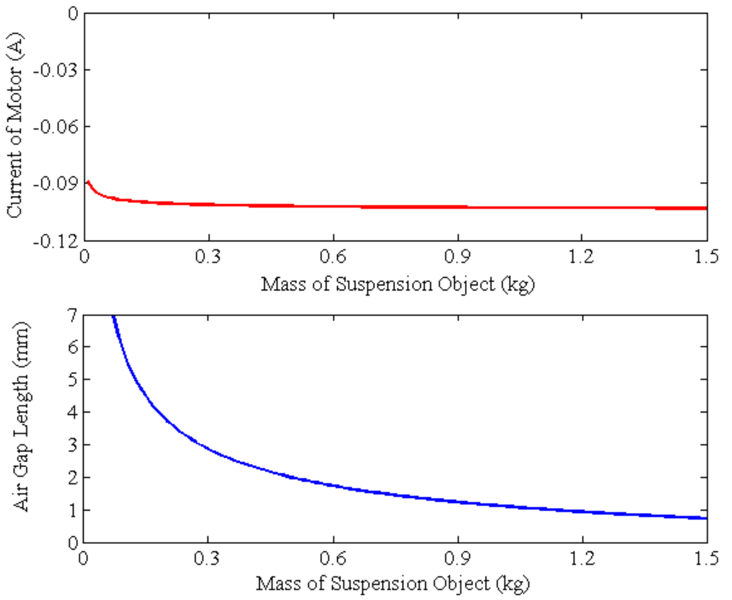

Figure 5: Simulation results with changing air gap length

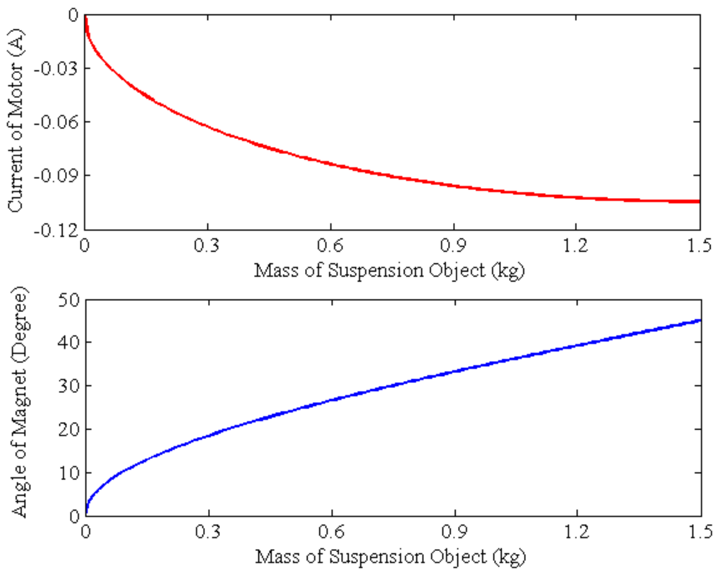

Figure 6: Simulation results with constant air gap length

4.2 Analysis in Simulation

Basing on the mathematical model, the semi-zero power control was analyzed by simulation. In the simulation, first, when the mass of the suspension object was increased from 0 to 1.5 kg and the angle of magnet was set to 40 degree as constant, the air gap length and the current of motor was analyzed in the static suspension state; second, when the mass of the suspension object was increased from 0 to 1.5 kg and the air gap length was set to 0.9 mm as constant, the angle of magnet and the current of motor was analyzed in the static suspension state. The parameters using in simulations are shown in Table 1.

4.2.1 Semi-zero power control with changing air gap length

The simulation results when fixing the angle of magnet are shown in Figure 5. In the upper figure of Figure 5, the vertical axis expresses the current of motor, and the horizontal axis expresses the mass of suspension object. In the lower figure, the vertical axis expresses the air gap length between the iron core and the suspension object, and the horizontal axis is same with the one of upper figure.

Figure 5 indicates that the actuator current increases a little as the mass of suspension object are increased. When the rotational angle of magnet is maintained at same degree, the attractive force of the iron cores is constant. In this time, if increasing the weight of the suspended object and maintaining the suspended object in the stable suspension state, the length of air gap between the suspended object and the iron cores decreases. As the length of air gap decreasing, the potential force of magnetic field is increased. Therefore, the current of the rotary actuator increases a little while the weight of the suspended object is increased. However, the current of the motor is very small. The maximum value is about 0.1 A. At the same time, the air gap becomes small. Comparing the current consumption with the weight of the suspended object, the semi-zero power suspension characteristic with changing air gap, and the minus stiffness characteristic of this suspension mechanism are affirmed, which are same with the general zero power magnetic suspension systems with an electromagnets.

4.2.2 Semi-zero power control with constant air gap length

The simulation results when fixing the air gap length are shown in Figure 6. The vertical axis of lower figure in Figure 6 expresses the rotational angle of magnet, and others are same with those of Figure 5. From Figure 6, we can see that, when the mass of suspension object increases, the larger suspension force will be needed. Since the air gap length is set up to 0.9 mm, the suspension force can be increased through increasing the rotational angle of magnet as shown in the lower figure. In the upper figure, the actuator's current increases with the increasing mass of suspension object. When the mass of suspension object is 1.5 kg, the consumption current is about 0.1 A, which is a quite small current comparing with the suspension load. These results are also consistency with Figure 4.When the angle is increased until 45 degrees, the torque of magnet increases, and the consumption current of actuator is used to counteract the torque of magnet. These results indicate the semi-zero power control characteristics with a constant air gap length.

4.3 Analysis in Experiment

Moreover, the semi-zero power control was also analyzed in experiment. In the experiment, first, the rotational angle of magnet was set to 40 degrees. When the suspension object with the mass of 1.44 kg was suspended stably, the air gap length and the 10 seconds current of actuator were recorded, and the average current was calculated

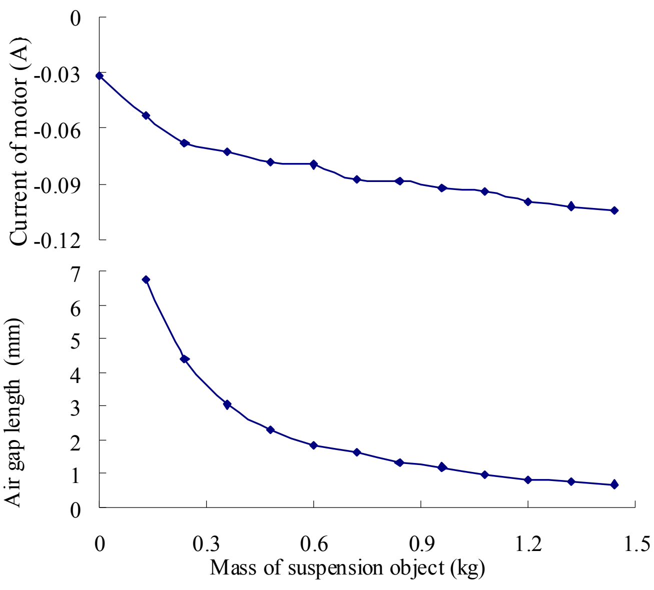

Figure 7: Experimental results with changing air gap length

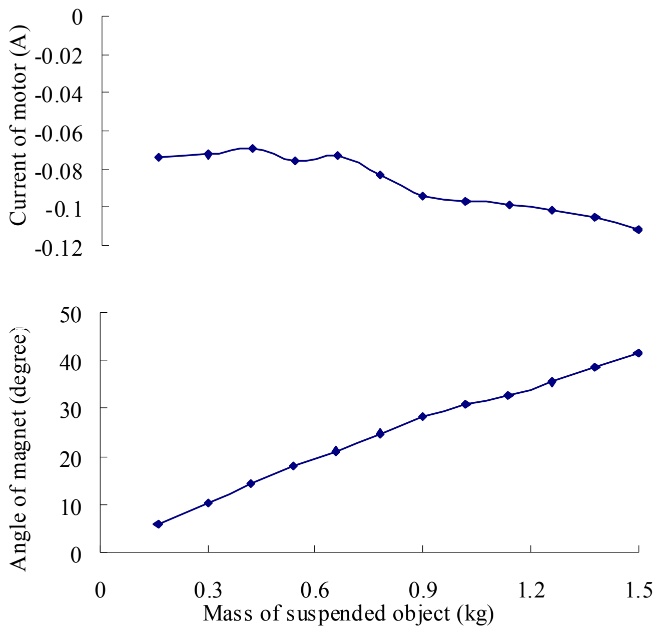

Figure 8: Experimental results with constant air gap length

basing on the recorded current data. Moreover, the mass of suspension object was reduced with a step of 0.12 kg until the mass equaled to 0.13 kg, and the average current was calculated in every step. Second, when the air gap length was set to 0.9 mm, the process of first experiment was repeated, and the rotational angle and average current of actuator were also recorded.

4.3.1 Semi-zero power control with changing air gap length

The first experiment results are shown in Figure 7. The upper figure shows the relationship between the current of motor and the mass of suspension object, and the lower figure shows the relationship between the air gap length and the mass of suspension object. The air gap length graph is almost same with the one in Figure 5, but the current graph is different from the one in Figure 5. The difference may be caused by the noise and the effect of the friction in mechanism. However, the maximum current is almost same with the simulation results.

4.3.2 Semi-zero power control with constant air gap length

The second experiment results are shown in Figure 8. These results are also consistent with the simulation results. The current and the angle increase with the increasing mass of suspension object. Even there are some differences between the experimental results and simulation results, we also can see that, the current of actuator is nonzero, but the maximum value of current is about 0.1 A, which is quite small. Therefore, the semi-zero power control with a constant air gap length can be understood from these results.

The semi-zero power control with a constant air gap length characteristic can realize the suspension of mechanism with advantages of the save-energy suspension and the safe suspension with a constant air gap length.

5 Conclusion

This paper introduced the principle of variable flux path control mechanism and the experimental prototype, and analyzed the semi-zero power control characteristics of the proposed permanent magnetic suspension mechanism. The analysis was done in mechanism, in mathematical model, in simulation, and in experiment. All the analysis and results indicated that this magnetic suspension mechanism could realize not only semi-zero power suspension with changing air gap but also semi-zero power suspension with a constant air gap. The semi-zero power suspension characteristics can realize both the save-energy suspension and the safe suspension at the same time.

ACKNOWLEDGMENT

A part of this research was done in Koichi University of Technology, Japan; a part of work was done in Shenyang University of Technology, China, and was supported partly by National Natural Science Foundation of China (Grant No. 51105257), the Doctoral Found of Liaoning Province of China (Grant No. 20111042), and the Doctoral Found of Shenyang University of Technology.

References

[1] MORISHITA M. and AZUKIZAWA T., "Zero Power Control Method for Electromagnetic Levitation System", Trans. IEE of Japan, Vol.108-D, No.45, 1988, pp.447-454.
[2] NOH M. D., ANTAKI J. F., RICCI M., GARDINER J., PADEN D., et al, "Magnetic Design for the PediaFlow Ventricular Assist Device", Artificial Organs Vol.32, No.2, 2007, pp.127-135.
[3] MIZUNO T., HIRAI Y. and ISHINO Y., "Flux-Path Control Magnetic Suspension System Using Voice Coil Motors", Journal of System Design and Dynamics, Vol.1, No.2, 2007, pp.147-158.
[4] UENO T. and HIGUCHI T., "Zero-Power Magnetic Levitation Using Composite of Magnetostrictive/Piezoelectric Material", IEEE Transactions on Magnetics, Vol.437, No.8, 2007, pp.3477-3482.
[5] SUN F. and OKA K., “Zero power control for hanging type maglev system with permanent magnet and VCM”，Trans. of JSME Series C, Vol. 75, No.753, 2009, pp.1383-1388.
[6] SUN F. and OKA K., “Development of Noncontact Suspension Mechanism Using Flux Path Control Disk Magnet Rotation”，Trans. of JSME Series C, Vol.76, No. 771, 2010, pp. 2976-2981.