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Characteristics Analysis of Magnetic Suspension Mechanism with Variable Flux Path Control

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Abstract: This paper proposes a magnetic suspension system using a disk-type permanent magnet and a rotary actuator. In this suspension system, the suspension force is controlled by a variable magnetic flux path mechanism where the flux path is changed by varying the angle of the magnet. This system has the characteristics of semi-zero suspension force, variable magnetic poles, and energy-saving suspension. In this paper, the variable flux path control method and an experimental prototype are introduced. Based on the results of the basic experiments, numerical simulation, and suspension experiments, the characteristics of the proposed mechanism are analyzed.

Keywords: Magnetic Suspension, Flux Path Control, Permanent Magnet, Rotary Motor

Introduction

So far, many magnetic suspension systems have been developed, and various control methods of suspension force have been proposed [1]. In the magnetic suspension systems using permanent magnets, there are mainly two control methods of suspension forces, which are the air gap length control and the variable flux path control [2]. Using the air gap length control, some magnetic suspension systems have been proposed for noncontact transmission and manipulation applied in the super-clean room [3,4]. Using the variable flux path control, the zero-power magnetic suspension system has been developed with the composite of magnetostrictive and piezoelectric materials [5]. Moreover, a flux path control magnetic suspension system has been reported with the motion control of a part of ferromagnetic yokes in a magnetic circuit [6]. However, most magnetic suspension systems have a disadvantage, which is once the suspended object adheres to the permanent magnets or the magnetic yokes, the suspended object cannot be controlled any more, unless another force is used to detach the suspended object from the magnets or magnetic yokes.

This paper proposes a magnetic suspension system using a disk-type permanent magnet and a rotary actuator [7]. In this suspension system, the suspension force is controlled by a variable magnetic flux path mechanism where the flux path is changed by varying the angle of the magnet. This system can generate a semi-zero suspension force, which can overcome the fore-mentioned disadvantage of the magnetic suspension system using permanent magnets. Moreover, this system also can realize the variable magnetic poles and an energy-saving suspension. In this paper, the variable flux path control method of the suspension forces and an experimental prototype are introduced. Based on the results of the basic experiments, numerical simulation, and suspension experiments, the characteristics of the proposed mechanism are analyzed.

Principle of Variable Flux Path Control Mechanism

The principle of variable flux path control mechanism can be understood from Fig. 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 90 [degree] and an S pole of opposite side 90 [degree] as shown in Fig. 1; (II) There is no flux leakage to the air in this magnetic suspension system. Fig. 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, Fig. 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.

Experimental Prototype

An experimental prototype of the proposed magnetic suspension system was constructed, and the photograph of the prototype is shown in Fig. 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 Fig. 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].

Basic Characteristics Examination

In order to examine the basic characteristics of the suspension mechanism, the magnetic flux density between the suspended object and two iron cores, the attractive force of two iron cores,

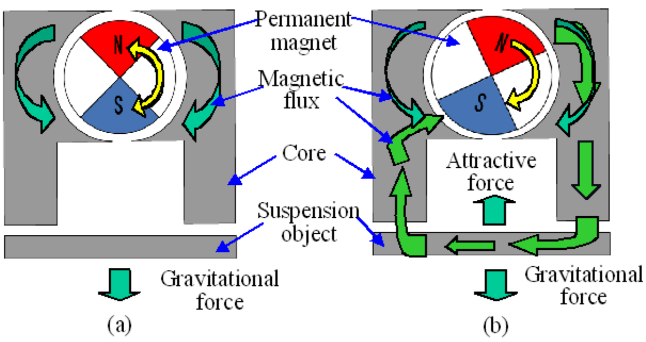

Fig. 1 Principle of variable flux path control

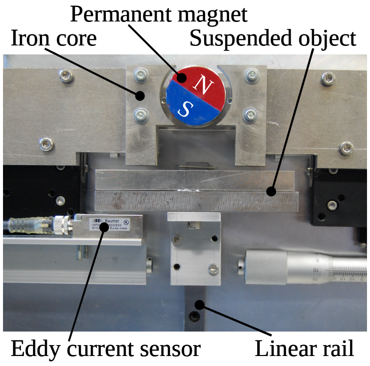

Fig. 2 Photograph of the prototype

and the rotational torque of magnet were measured. In the measurement experiment, the permanent magnet was rotated at 10 [degree] 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 magnetic flux density was measured when the air gap length varied from 3 [mm] to 10 [mm]. The attractive force and the rotational torque were measured when the air gap length varied from 2 [mm] to 8 [mm].

Examination of Magnetic Flux Density. The magnetic flux density between the suspended object and two iron cores was measured with gauss meters. Measured results of magnetic flux density are shown in Fig. 3 and Fig. 4. Fig. 3 shows the relationship between the magnetic flux density and the rotational angle of magnet. The graphs of magnetic flux density resemble sine curves according to the rotational angle of magnet at all air gap lengths, and the smaller distance yields greater magnetic flux density. Moreover, the magnetic flux direction is changing at about 180 [degree]. Fig. 4 shows the relationship between the magnetic flux density and the air gap. The graph indicates that the flux density is approximately in inverse proportion to the length of air gap.

Examination of Attractive Force. The attractive force between the suspended object and two iron cores was measured with a load sell. The measured results of attractive force are shown in Fig. 5 and Fig. 6. Fig. 5 shows the relationship between the attractive force and the rotational angle of magnet. In the figure, the force is expressed when the rotational angle of magnet is changing and the length of air gap is seemed as a parameter. The results indicate that, the attractive force varies as the rotational angle of magnet changes, and smaller distances yield

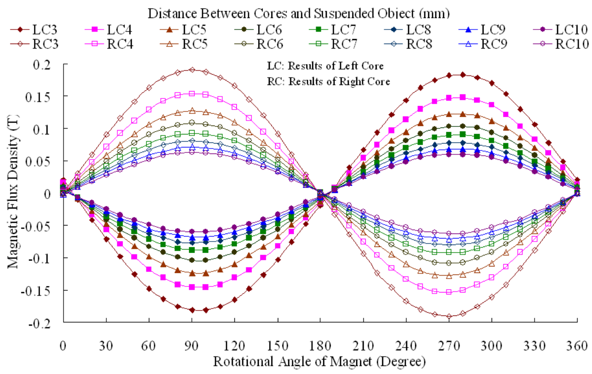

Fig. 3 Relationship between flux density and rotational angle

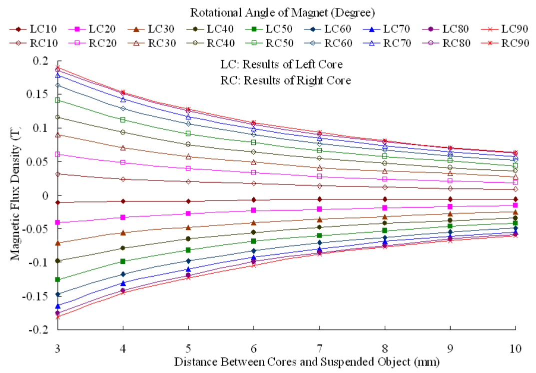

Fig. 4 Relationship between flux density and air gap

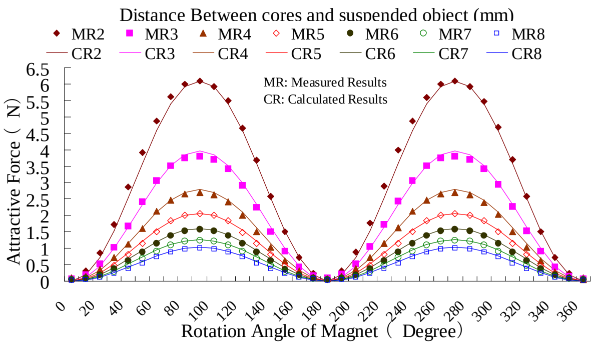

Fig. 5 Relationship between attractive force and rotation angle

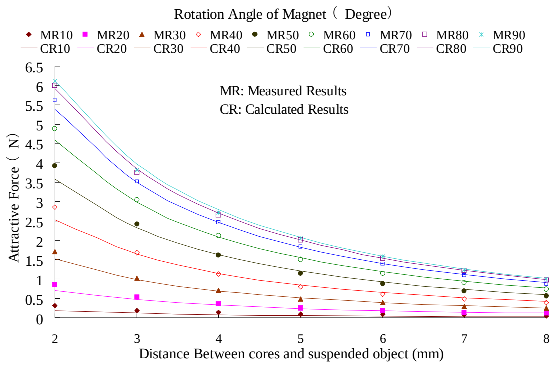

Fig. 6 Relationship between attractive force and air gap

greater attractive force. Moreover, the attractive forces are almost zero when the rotational angle is around 0 and 180 [degree], i.e. the N pole and S pole stop at directly above or below. The forces are maximums when the rotational angle is around 90 and 270 [degree]. Fig. 6 shows the relationship between the attractive force and the length of air gap. The figure indicates that the attractive force becomes large as the length of air gap becomes short.

In order to examine the semi-zero attractive force characteristic, the force was measured when varying the distance between magnet and cores and the distance between cores and the suspended object. Fig. 7 shows the results of attractive force when the distance between the permanent magnet and the iron cores is expanded to 10 [mm]. Comparing the results with Fig. 5, the attractive force at about 0 and 180 [degree] becomes large as the distance expands between the permanent magnet and the iron cores. This is caused by the magnetic flux leakage of the device. Fig. 8 shows the results of attractive force as varying the distance between magnet and cores and the distance between cores and the suspended object, when the rotational angle of magnet is at 0 [degree]. The results indicate the characteristic of the semi-zero suspension force as that smaller distance between cores and suspended object generates greater attractive force, and larger distance between cores and magnet generates greater attractive force.

Examination of Rotational Torque of Magnet. For examining the effect of the magnetic potential to the permanent magnet, the rotational 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

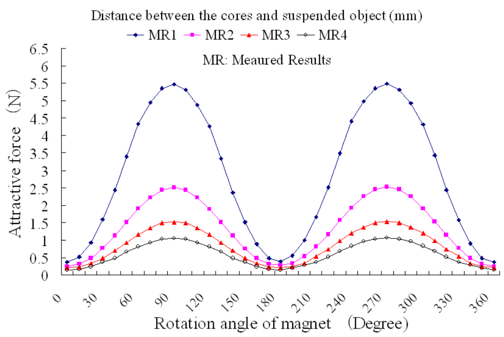

Fig. 7 Attractive force when the distance between magnet and cores is expanded

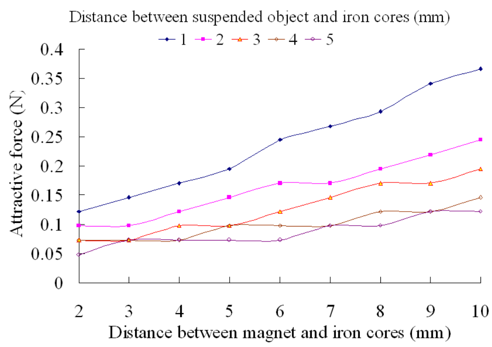

Fig. 8 Attractive force when magnet stops at 0°

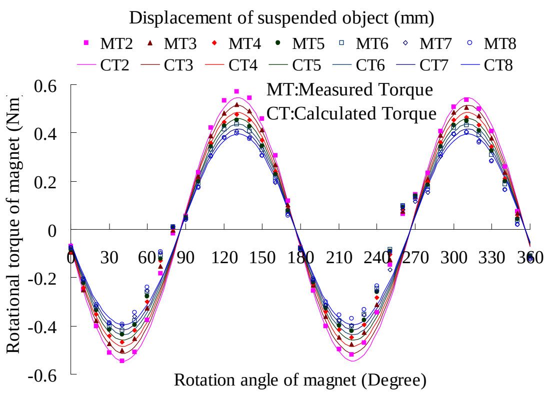

Fig. 9 Rotational torque of permanent magnet

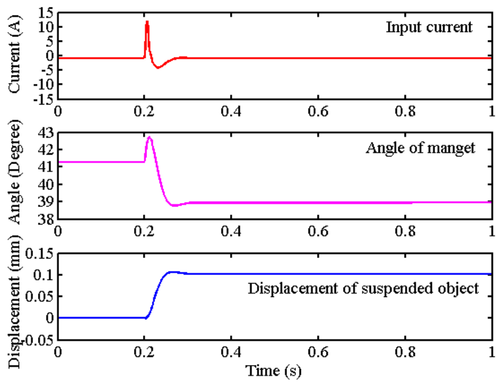

Fig. 10 Simulation results of suspension

on the side of the connector between the rotary motor and the permanent magnet, and the rotational torque was measured in the same condition with measurement experiment of attractive force. The measured results of the rotational torque are shown in Fig. 9. 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.

Mathematical Model of Suspension System

Modeling Suspension Force. According to the relationship of the flux density with the rotational angle θ and the length of air gap d shown in Fig. 3 and Fig. 4, and considering about the square relationship between the attractive force and the magnetic flux density, the attractive force f can be expressed as the following equation.

$$f = k_m \frac{\sin^2\theta}{(d + \Delta d_f)^2} \tag{1}$$

Where k_m is a proportionality coefficient of attractive force and Δd_f is a compensation coefficient of air gap. Comparing the attractive force calculated by Eq.1 with the measurement results, the coefficients k_m and Δd_f can be decided as 1.06×10^{-4} [Nm^2] and 2.17 [mm]. The comparison results shown in Fig. 5 and Fig. 6, where the solid line expresses the calculation force and the point mark expresses the measurement force. The comparison indicates that Eq. 1 expresses the measurement results of the attractive force very well, and the validity of attractive force model is proved.

Modeling Rotational Torque of Permanent Magnet. According to the results shown in Fig. 9, the rotational torque of magnet τ can be expressed by the rotational angle θ and the air gap d as the following equation.

$$\tau = k_\tau \frac{\sin 2\theta}{d + \Delta d_\tau} \tag{2}$$

Where k_τ is a proportionality coefficient of rotational torque and Δd_τ is a compensation coefficient of air gap. The coefficients k_τ and Δd_τ can be obtained from Fig. 9 as -8.726×10^{-3} [Nm^2] and 14 [mm].

Motion Equations of Motor and Suspended Object. Using the mathematical model of the attractive force and the rotational torque of magnet and assuming the displacement of the suspended object as z in the upward direction, the motion equations of the motor and the suspended object can be expressed as:

$$J\ddot{\theta} = c_1\dot{\theta} + k_\tau \frac{\sin 2\theta}{d + \Delta d_\tau - z} + k_t i \tag{3}$$

$$m\ddot{z} = c_2\dot{z} + k_m \frac{\sin^2\theta}{(d + \Delta d_f - z)^2} - mg \tag{4}$$

Where, J is the moment of inertia of motor and magnet; k_t is the torque constant of motor; 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.

Suspension Characteristics

Numerical Simulation. In order to examine the feasibility of suspension, a numerical simulation using the motion equations is implemented. In the simulation, the nonlinear attractive force and the nonlinear rotational torque are used directly, and the mass of suspended object is 1 [kg]. An input disturbance of a step of 0.05 [mm] was applied to the displacement of the suspended object, and the response was recorded until 1 [s]. The results of the response are shown in Fig. 10. The figure shows the input current of motor, the angle of magnet, and the displacement of suspended object from up to down. As shown in Fig. 10, after applying the disturbance, the system returns to stable state quickly, and the current is very small in the stable state.

Experimental Results. Using the experimental prototype shown in Fig. 2, the suspension has been succeeded. The step response results are shown in Fig. 11 when the mass of suspended object is 1 [kg]. In the figure, the input current, the rotational angle of magnet, and the displacement of suspended object are recorded from 1 to 2 [s]. The results indicate that the suspended object can be suspended stably and the input current is almost zero at the stable state. That means this magnetic suspension mechanism can suspend a heavy object by means of a small input force, since the gravitational force of suspended object is sustaining by the cores fixed on the frame. Therefore, this system can realize an energy-saving suspension.

Energy-saving Suspension Characteristic. In order to analyze the energy-saving suspension performance of the suspension mechanism, the variation of the actuator current was examined when the weight of suspended object was changed. In the experiment, the angle of magnet was adjusted to 40 [degree] each time after the suspended weight was changed, and the actuator current was measured. The mass of the suspended object was changed from 0 to 1.35 [kg]. The simulation also was carried out with the mathematical model. In the simulation, the suspended object of 0 [kg] was instead of 0.02 [kg]. The simulation and experiment results are shown in Fig. 12. The results indicate that the actuator current increases as the mass is increased. If 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

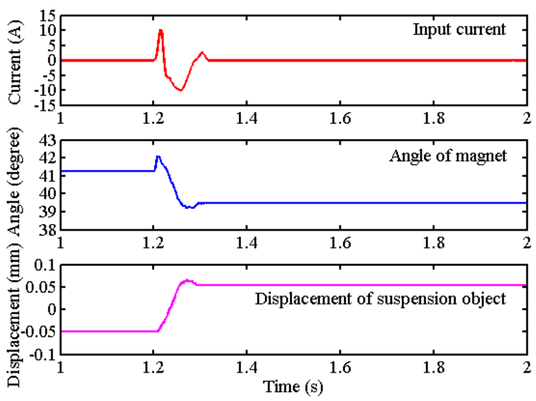

Fig. 11 Experimental results of step response to the suspended object

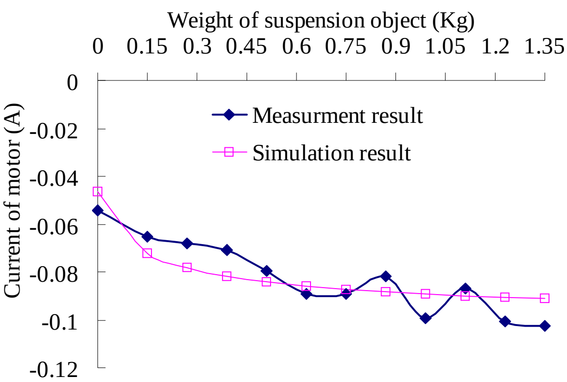

Fig. 12 Relationship between motor current and mass of suspended object

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 filed is increased. Therefore, the current of the rotary actuator increases while the weight of the suspended object is increased. However, comparing the current consumption with the weight of the suspended object, the energy-saving suspension characteristic of this suspension mechanism is affirmed.

Conclusion

This paper introduced the principle of variable flux path control mechanism and the experimental prototype. The basic experiments, numerical simulation and suspension experiment were carried out. The mechanism's characteristics that are semi-zero suspension force, variable magnetic poles, and energy-saving suspension, have been analyzed based on the simulation and experiment results.

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