Magnetic Suspension System with Variable Flux Path Mechanism Using Rotary Actuator*

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***Abstract*— This paper describes a novel type of magnetic suspension system with a permanent magnet and a rotary actuator. The feature of this suspension system is that a rotary actuator controls attractive force. Varying the angle of the permanent magnet driven by the actuator changes magnetic flux path in the suspension system and controls the suspension force. The merits of this suspension system are that the attractive force of this magnetic circuit can be made to be zero. Moreover this system can change the polarity of stator poles. First an outline of the suspension system will be described. Next, the principle of the suspension mechanism will be explained. To verify the feasibility of the proposed system, some basic experiments, a numerical simulation, and an experimental result will be shown.**

***Index Terms*— Magnetic suspension system, Variable flux path, Rotary actuator, Permanent magnet**

I. Introduction

There are many kinds of mag-lev systems which have been investigated and developed [1]. All most of such kinds of mag-lev systems are EMS(electromagnetic suspension) systems which use electromagnets for controlling suspension forces by adjusting currents of their coils. There exist, however, some kinds of mag-lev systems which do not use electromagnets but permanent magnets [2]–[6]. These mag-lev systems use permanent magnets as sources of magneto motive forces and controlling mechanisms of adjusting suspension forces.

Reference [2] proposed that reluctance control mechanism is used for suspension control. A voice coil motor type actuator actuates a permanent magnet and controls suspension force. Reference [3] proposed that control of the air gap length adjusts the suspension forces. A piezoelectric actuator actuates a permanent magnet. Reference [4] uses repulsive force for levitation. Repulsive force between permanent magnets is used as a source of magnetic force and it is controlled by a voice coil actuator. Reference [5] proposed a mechanism of a flux path control in mag-lev system. A positioning system which is made by electromagnets is used for changing the flux path. Reference [6] proposed that a magnetostrictive and piezoelectric device uses for levitation. Magneto motive flux by magnetrostrictive/piezoelectric device changes flux amount of the suspension system.

These mag-lev systems adjust their suspension forces by motion control mechanisms. And these suspension systems have common problems. One is that suspension forces can not set to be zero. Once a suspended object adheres to stator parts, there is almost no way to come back to the suspension state. Another problem is that such a suspension mechanism can not change the polarity of the stator. These problems come from the mechanism that these suspension mechanisms use permanent magnets.

A novel type of suspension system which can make the suspension force to be zero is proposed. Moreover the polarity of the stator can be changed. The proposed mechanism uses a rotary actuator and a permanent magnet. The angle of the permanent magnet is controlled by the actuator and the movement changes flux amount of a suspension system. Flux control mechanism has already proposed by [2], [5] and [6]. However, the proposed method changes the flux path essentially. So this method can change the polarity. In this paper, a prototype suspension system is introduced and the principle of the suspension mechanism is explained. Basic experimental results about attractive forces and flux density is shown. Based on the results, a numerical simulation is calculated. An experimental examination is carried out and succeeded. These results verify the feasibility of the proposed mag-lev system.

II. Suspension System with Rotary Actuator and Permanent Magnet

A prototype suspension system has been made to verify the the proposed suspension system. In this section, this suspension system will be explained.

A. *Prototype suspension system*

An illustration of the proposed suspension system is shown in Fig. 1, and a photograph of the device is shown in Fig. 2. As shown in the figures, the system consists of a rotary actuator, a permanent magnet(PM), two iron cores, and a levitated object. The circle of the center of the middle in the figure is a PM. An N pole and an S pole on the PM are magnetized in the direction of a diameter. In Fig. 1, the PM is magnetized in the horizontal direction.

The PM is actuated in the rotary direction by an actuator behind a wall. In Fig. 2, the actuator can not be seen. The actuator has an encoder which measures the angle of the PM. Two cores, one of them is a shape of character

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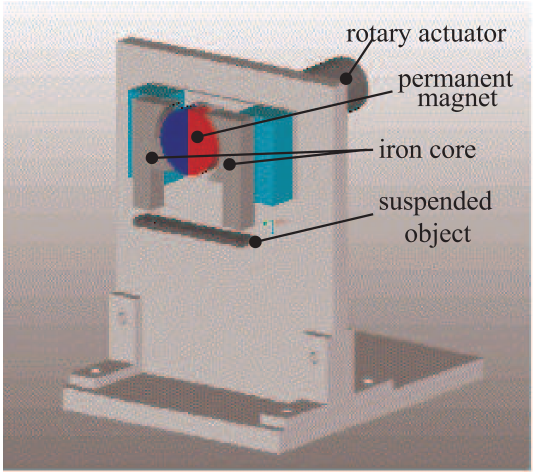

Fig. 1. Illustration of a proposed suspension system with rotary actuator and permanent magnet.

F and the other is inverse F, are installed on the wall as surrounding the PM. The role of these cores is transfering flux from the PM to a suspended object.

The suspended object is a plate which is located under cores. In the experimental device, the plate is supported by mechanical bearings as shown in Fig. 2. It can move like a lever around a fulcrum. This restriction of the degrees of freedom makes it easy to measure the characteristics of suspension. The position of the suspended plate is measured by an eddy current sensor which is located under the plate and is emitted in the figures.

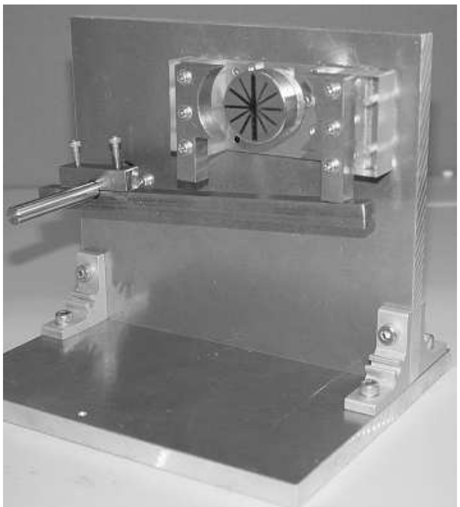

Fig. 2. Photograph of a prototype suspension system.

B. Configuration of Suspension System

The control system configuration for the prototype is shown in Fig. 3. The controller is a DSP controller and feedbacks the signals of the angle of the PM and the displacement of the object. The angle is sensed by an encoder installed in the rotary actuator(DC motor) and the displacement is sensed by an gap sensor. These signals are converted to digital values by a counter and an A/D converter. Based on the values, a DSP in a PC calculates the voltage for the DC motor and controls the angle of the magnet through a D/A converter and an amplifier.

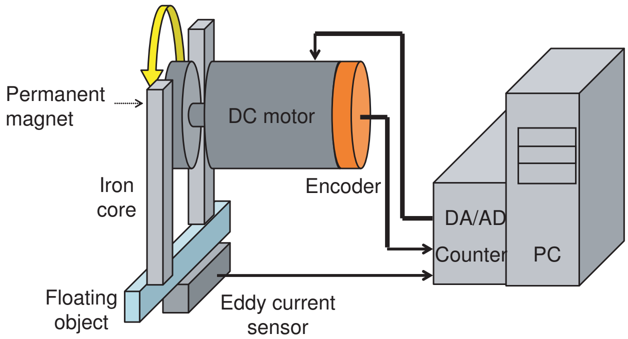

Fig. 3. Illustration of control system for a prototype suspension system.

III. Principle of Proposed Suspension System

To realize stable levitatation of the object by the proposed suspension system, a magnetic force control mechanism is needed for the system by rotating of the PM. The principle of the mechanism is explained using Fig. 4. This figure shows the front view of the system. We assume followings. One is that the magnet has an N pole of 90 degrees and an S pole of opposite side 90 degrees as shown in the figure. Second, there is no flux leakage to air.

We consider about the situation that the direction of the magnetization of the PM is aligned to the vertical as shown to the left figure(Fig. 4 (a)). The left half of the magnetic flux which comes out from the N pole is considered to flow through the left side iron core and absorbed to the left side of the S pole. The right half of the flux from the N pole may flow in the right core and absorbed to the right S pole. In this case, all flux from the N poles flows only in iron cores and the magnetic flux does not pass through the object. There are no attractive force for the object.

When the motor rotates the magnet and the direction of the magnetization becomes inclined as shown in Fig. 4 (b), the grater part of the magnetic flux from the N poles flows through the right side iron core. A part of this flux passes through in the right side core with drawing a small arc and is absorbed to the right S pole where is facing to the core. However, because of the difference of the area of the core facing to the N pole and facing to the S pole, the rest of this flux can not be absorbed to the right S pole through the right side core only. On the other hand, in the left side core, as the area facing to the S pole is larger than the area facing to the N pole, there is lack of magnetic flux for absorption at the S pole. As the results, the flux coming out of the right N pole passes through the suspended object and is absorbed to the left side core and returns to the S pole of the magnet. This magnetic flux pass through the object generates the attractive force for the object.

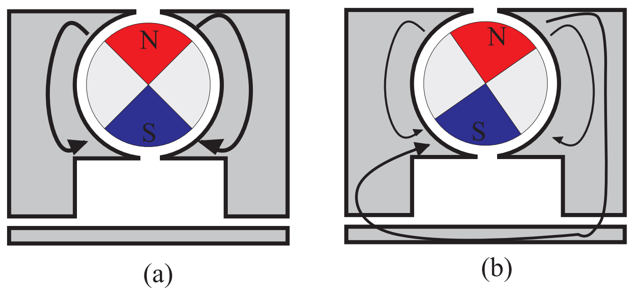

Fig. 4. Two types of flux path by difference angle of permanent magnets.

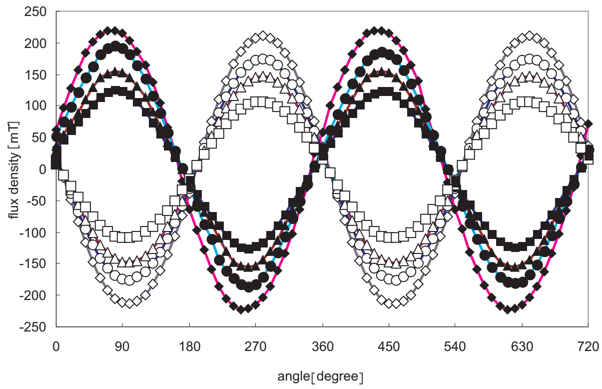

Fig. 5. Flux density about angle of PM and length of air gap.

As the attractive force for the suspended object is generated by the flux through the air gaps, the force can be controlled by the amount of the passing flux which is caused by the difference of the area of the left and the right core facing to the N pole and the S pole. The larger the angle inclines, the larger the flux passes through the plate. It means that the angle of the PM controls the attractive force. From the state of Fig. 4(a), as the angle of the PM becomes larger, the flux passing through the object becomes also larger and the maximum angle is 90 degrees when the N pole lies in the horizontal direction. The more rotation causes decreasing of the flux passing through the object. When the N pole is located at just under the center, the flux disappears again. And more rotation makes the direction passing through the object become inversely. Thus, the proposed suspension mechanism not only control the flux but change the polarity of the stator core. The attractive force is changes zero, maximum, zero, maximum, zero as the PM rotate in one revolution. We call the mechanism as variable flux path.

IV. Basic Examination of Prototype System

Two basic examination were carried out on the system to obtain the characteristics of the prototype suspension system. One is flux density about the magnet angle, and the other is attractive force.

A. Relationship Between PM Angle and Flux Density

The attractive force can be calculated by the amount of flux passing through the air gap. As an index of the amount of the flux, the flux density at the air gap between the iron core and the object has been measured about the angle of the PM and the length of air gap. The measurement has been done from 0 degree to 720 degrees by 10 degrees step for the PM angle and 0.5 mm step for the air gap length.

The results are shown in Fig. 5. The black signs indicate the flux density between the left core and the object and the white signs indicate the right core. The largest amplitude curve is the result of 0.5 (mm) air gap. and the smallest one is 2 (mm). As shown in the figure, each flux density varies like sine curve. As the result, it is verified that the rotation of the PM can control the flux, make the flux to be zero, and change the direction of polarity.

B. Relationship Between PM Angle and Attractive Force

The attractive force has been measured about the angle of the PM. A force sensor which was attached to the object sensed the attractive force by the angle of 30 degrees step and the air gap length of 1 (mm) step from 1 (mm) to 7 (mm).

The results are shown in Fig. 6. As shown in the figure, each line varies according to the PM angle and has 2 minimum points and 2 maximum points in one revolution. The larger air gap makes the smaller attractive force. We expected that the line of the force has the point of 0 (N). Fig. 6, however, has not such a point. The fact is shown by Fig 5. The point at which the flux flows from the left core is not same as the point that the flux of the right core is zero. The reason may be that there is some leakage in the magnetic flux path and the magnetization of the PM is not uniform. But, as the aim of this paper is the stable suspension of the proposed suspension system, these problems may not affect the levitation of the object.

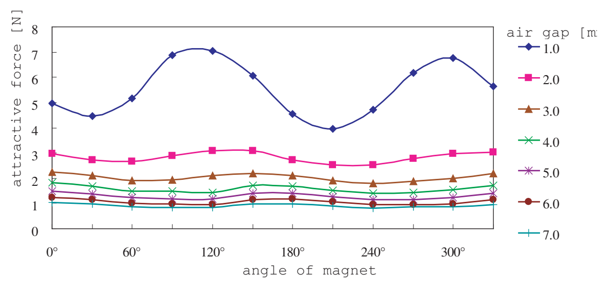

Fig. 6. Attractive force about angle of PM and length of air gap.

V. Numerical Simulation

To verify the feasibility of the proposed suspension system, a numerical simulation was carried out on the model based on the parameter of the above section. For modeling the followings has been assumed, *i*) the one half part of the PM is the N pole and the other part is S pole, *ii*) the flux coming out from the PM and absorbed to the PM is in proportion to the area facing to the iron core, *iii*) the magneto-resistance of the iron core is enough small and there is no leakage of flux.

Symbols using in the modeling are, θ: the angle of the PM, z: the displacement of the suspended object, Q: flux passing through the object, (positive is from left to right), d the length of air gap, m: the mass of the suspended object. When the lower half of the PM is the N pole and upper half is the S pole, the angle θ is zero. The flux passing through the object is represented by the equation

$$Q = k \sin\theta/(2d) \quad (1)$$

where k is a constant. The attractive force is considered in proportion to the square of the flux. The motion equation of the suspended object is

$$m\ddot{z} = Q^2 - mg = k'\frac{\sin^2\theta}{d^2} - mg. \quad (2)$$

Numerical Simulation of step response is carried out by Eq. (2), where, the movement of the PM is controlled by its velocity and neglect the friction of the system. The result is shown in Fig. 7. As shown in the figure, stable levitation is realized before and after a step input. Hence, the feasibility of the proposed suspension system has been verified.

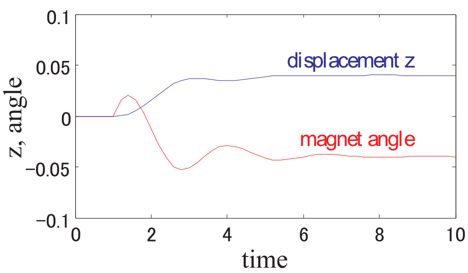

Fig. 7. Numerical Simulation When the Step Input is Applied for Suspension System.

VI. Examination of Prototype System

The experimental levitation was carried out on a prototype suspension system and succeeded. A photograph during levitation is shown in Fig. 8. In the prototype system, the levitated object is a lever and supported by a mechanical bearing except the direction of levitation. In the figure, the upper left circle is the magnet, the bar from the left side to the photo is the suspended object. The system may use only right side core for levitation. There is a gap sensor under the object.

The step response examination was also carried out. The result is shown in Fig. 9. Three lines indicate the angle of magnet, the displacement of the object, and the applied voltage for the DC motor. The step input was added to the angle of the motor at about 0.12 [s]. After that, the angle and the displacement are converged to the different values from the initial position. However, the stability is continued. The average of the voltage of the motor is zero before the step input and after. The reason is that the motor torque does not support the object directly in the system. It may prove the zero power control. There are residual vibration, especially the angle and the voltage. They may be caused by the friction of the bearings of the motor and the object. As the result, the levitation experiment was succeeded.

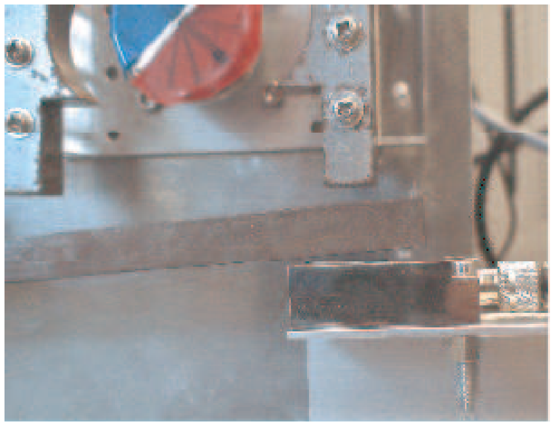

Fig. 8. Photograph when prototype suspension system is levitating.

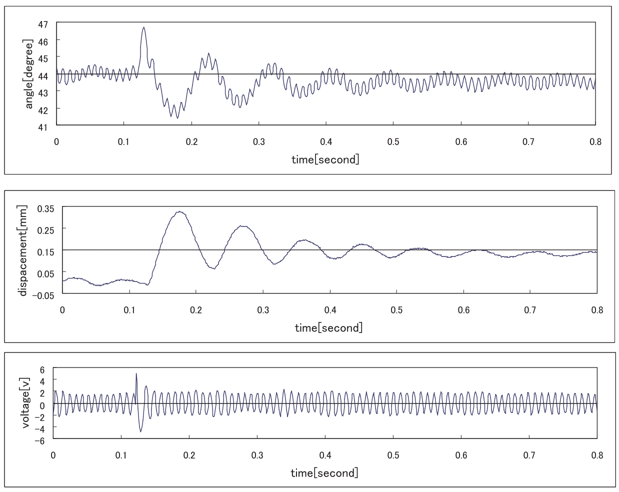

Fig. 9. Results of step response.

VII. Conclusion

A novel magnetic suspension system using a rotary actuator and a permanent magnet was proposed. The system may solve the problem that the suspension force of similar systems can not set to be zero. Moreover the suspension system can realize zero power control. The outline of the suspension system was introduced and the principle of the suspension was explained. Measurements of the force and the flux density about air gap and the magnet angle on a prototype can not verify that the attractive force can be set to zero. However noncontact levitation was succeeded and the feasibility of the proposed system was verified.

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