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Improvement Methods of Zero Suspension Force Performance of Variable Flux Path Control Device

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This paper proposes some improvement methods of zero suspension force performance for a magnetic suspension device, which consists of a disk-type permanent magnet, two “F” type permalloy iron cores, and a suspended object. The zero suspension force of a permanent magnetic suspension device is indispensable for floating off when the suspended object is stuck on accidentally. Generally, the magnetic suspension system using permanent magnet is difficult to realize the zero suspension force, since the permanent magnet cannot make its attractive force zero. However, the magnetic suspension device has realized a semi-zero suspension force. The zero suspension force performance will effect the floating off stability. In order to improve the zero suspension force performance, this paper focuses on some improvement methods, such as flux leakage path cutting off method by inserting a magnetization material, changing magnetic source method by using a special permanent magnet, and flux path extending method by using two extended iron cores. The suspension force performance using these three methods were examined by experiments. The experimental results will be shown, and compared with each other.

Keywords: magnetic suspension, permanent magnet, zero suspension force, variable flux path control.

1. Introduction

Until now, many magnetic suspension devices have been proposed, and applied in many fields [1]. Most of these magnetic suspension devices are using electromagnet whose attractive force can be controlled by its current. We call the attractive force used to suspend an object or a device as the suspension force in the magnetic suspension system. When the current is zero, the suspension force of the electromagnetic suspension (EMS) device is zero. The zero suspension force of magnetic suspension device is indispensable for floating off when the suspended object is stuck on accidentally. However, the EMS has some disadvantages of heat generation, high-energy consumption, big coil size, and so on.

With the development of magnetic material, the attractive force of the permanent magnet becomes very strong [2]. Many researchers focus on developing magnetic suspension systems using permanent magnets. Morishita and Azukizawa have proposed a zero-power magnetic suspension system using the hybrid electromagnet with the permanent magnet and the coil [3], but the system had to use the large countercurrent to counteract the attractive force of the permanent magnet, when the system needed the zero suspension force. For 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 [4]. Ueno and Higuchi presented a zero-power magnetic levitation technique using a composite of magnetostrictive and piezoelectric materials [5]. The authors have proposed a hanging type magnetic suspension system using a permanent magnet and an actuator [6]. All the permanent magnetic suspension systems mentioned above are difficult to generate the zero suspension force.

However, the authors also have proposed a magnetic suspension system using a disk-shape permanent magnet and a rotary actuator [7]. In this system, the suspension force was controlled by a variable flux path control mechanism, and the zero suspension force could generate in some conditions, theoretically. Whereas there was magnetic leakage, the zero suspension force was not zero exactly.

Therefore, this paper proposes some improvement methods to decrease the zero suspension force of the original magnetic suspension system. In this paper, the magnetic suspension device and the suspension principle are introduced, and the improvement methods are proposed, which are flux leakage path cutting off method by inserting a magnetization material, changing magnetic source method by using a special permanent magnet, and flux path extending method by using two extended iron cores. Finally, the suspension force performance using these three methods were examined by experiments.

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2. Prototype and Suspension Principle

2.1 Experimental Prototype

The proposed experimental prototype is shown as Fig.1. This prototype consists mainly of a disk-type permanent magnet, a rotary actuator containing a gear

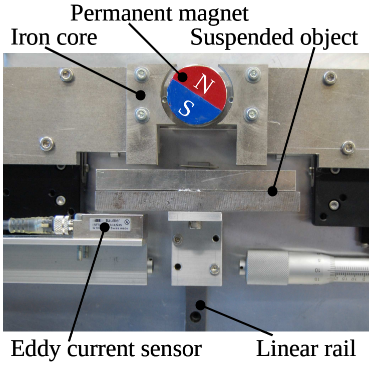

Fig. 1 Experimental prototype

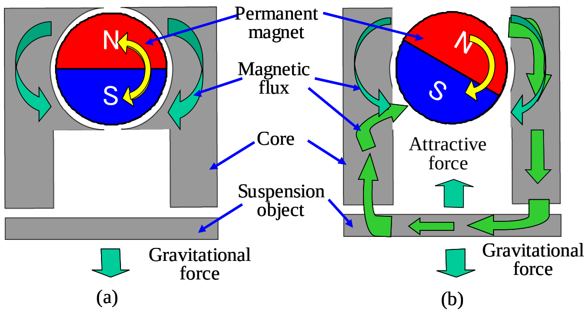

Fig. 2 Suspension principle

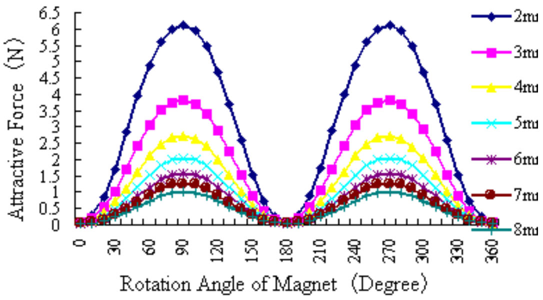

Fig.3 Attractive force between cores and suspended object using original magnet

reducer and an encoder, a pair of opposite "F" shape permalloy cores, a suspended object and an eddy current sensor. The magnet that is located in the opposite "F" shape 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 same as the magnet. The suspended object is installing on a linear rail, and can move in the vertical direction only.

2.2 Suspension Principle

The suspension principle can be understood from Fig. 2. 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 there is no flux leakage to the air in this magnetic suspension system. Fig. 2 (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. Therefore, the zero suspension force can be realized in this situation. However, Fig. 2 (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.

3. Existing Problem

In order to understand the suspension force performance of the magnetic suspension device, the attractive force between the suspended object and two iron cores was measured with a load sell, when the air gap length varied from 2 mm to 8 mm. The measured results of attractive force are shown in Fig.3. Fig.3 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 greater attractive force. Moreover, when the rotational angle is around 0 and 180 degrees, i.e. the N pole and S pole stop at directly above or below, the attractive forces are approaching to zero, but not zero.

In order to understand the reason that the suspension force is not zero, the magnetic flux field of the device was analyzed using IEM (Integral Element Method) analysis. The analysis result is shown in Fig.4. In the figure, the direction of arrows express the direction of the magnetic flux, and the size of the arrows express the intensity of the magnetic flux density. The magnetic flux that comes from N pole of the magnet almost returns to the S pole only through the upper side of the iron cores, and there is a little part of magnetic flux flows through the lower side of the iron cores, the suspended object, and the air space, finally returns to the S pole. Therefore, the attractive force between the iron cores and the suspended object is not zero. This problem is caused by the magnetic leakage between the magnet

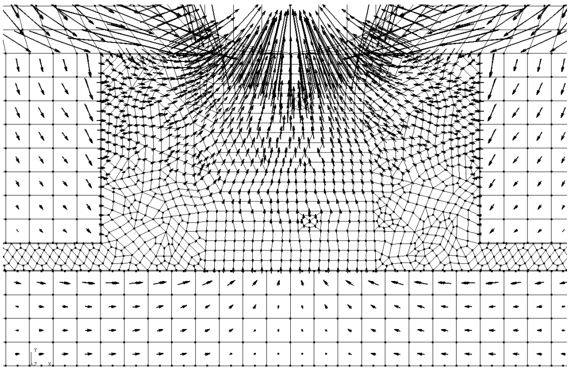

Fig.4 Magnetic flux field analysis of original device using IEM

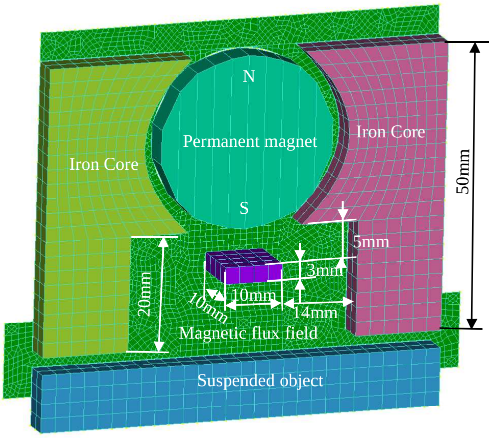

Fig.5 Inserting ferromagnetic board method

and the suspended object.

4. Proposed Improvement Methods

According to the analysis above, some improvement methods are proposed to decrease the magnetic leakage between the magnet and the suspended object.

4.1 Inserting Ferromagnetic Board Method

Fig.5 shows the schematic representation for inserting ferromagnetic board method. The model in this schematic representation is same with the experimental prototype shown in Fig.1 in dimensions, and a ferromagnetic board is inserted to the air space between the magnet and the suspended object. The inserted board is an iron board, whose size is 3x10x20 mm. In Fig.5, since the half model can be seen, a half part of the inserted board can be seen in the length direction also. The distance from the magnet to the inserted board is 5 mm, and the distance from the inserted board to the iron cores is 14 mm. The aim of inserting the iron board is to interdict the direct magnetic flux path from the magnet to the suspended object.

4.2 Using Special Permanent Magnet Method

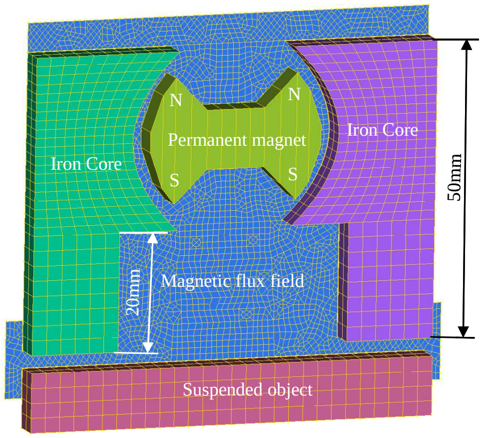

Fig.6 Using special magnet method

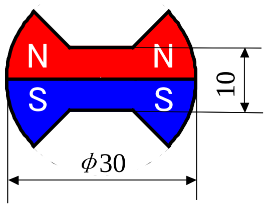

Fig.7 The special shape permanent magnet

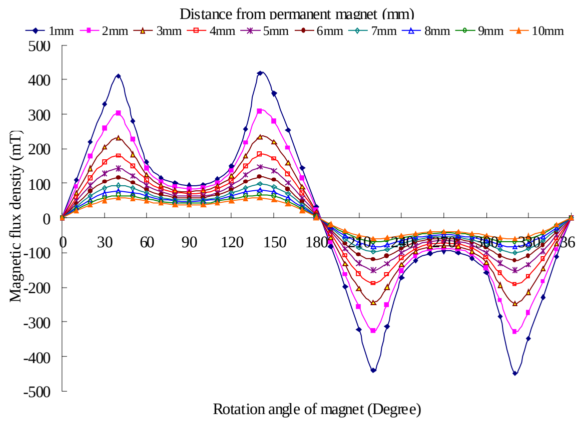

Fig.8 Magnetic flux density of the special magnet

4.2.1 Improvement method

Fig.6 shows the schematic representation for improvement method using a special shape permanent magnet, which is shown in Fig.7. The special magnet is the one cut off two 90-degree parts from the original round magnet shown in Fig.1, but the diameter and thickness are same with the original round magnet. The breath of middle remnant of the special magnet is 10 mm. The material of this magnet is neodymium.

Fig.8 shows the experimental results of magnetic flux field around the special magnet. The results show that the magnetic flux density varies as falling off between two pick periods, which is similar to the shape

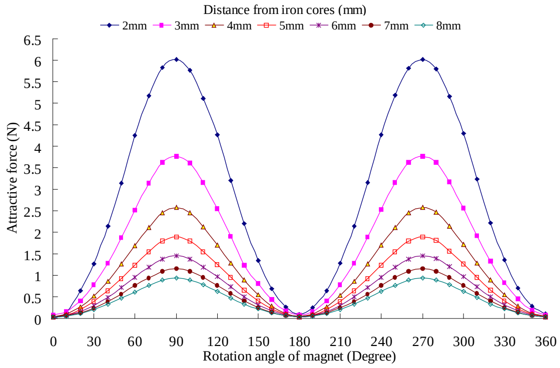

Fig.9 Experimental result of attractive force using the special permanent magnet

of the saddle. Therefore, if using this special magnet to replace the original round magnet, when the magnetic poles of this special magnet stop at the vertical direction, the leakage of the magnetic flux from the magnetic poles will be much less than that in original mechanism using the round magnet.

4.2.2 Experimental results of suspension force

In order to know the suspension force performance of the improved device using the special permanent magnet that has the magnetic performance shown as Fig.8, the attractive force between the iron cores and the suspended object was examined by the measurement experiment. The examined results are shown in Fig.9. The attractive force from the iron cores also resembles to the results of the original device, but the graph shape becomes thin, and the linearity of the attractive force becomes good towards to the rotational angle of the magnet. The results indicate that the rotation of the angle of the special magnet can control the suspension force, and the special magnet does not change the force performance of the magnetic suspension device. Moreover, it can be seen that the attractive forces at 0 degree and 180 degrees are smaller than the results of the original device.

4.3 Extending iron cores' length method

4.3.1 Improvement method

Fig.10 shows the schematic representation for extending iron cores' length method. The length of the iron cores is 80 mm in this model, which is 30 mm longer than the cores of the original mechanism. This method is going to reach the aim of reducing the leakage of the magnetic flux by extending the distance between the magnet and suspended object, i.e. enlarging the magnetic reluctance between the magnet and the suspended object.

4.3.2 Experimental results of suspension force

Fig.11 shows the measurement results of the attractive force using the extended iron cores. From the results, we can see that, the maximum force becomes

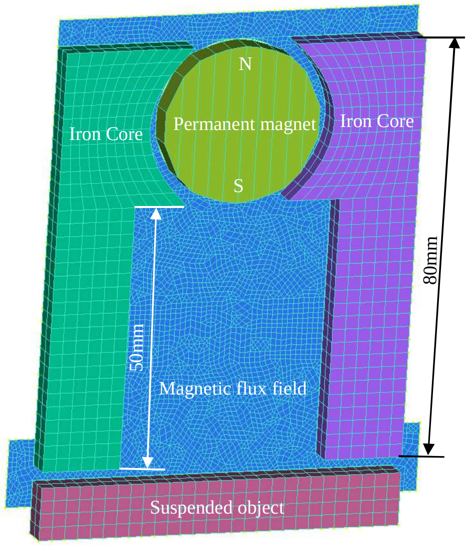

Fig.10 Extending iron cores' length method

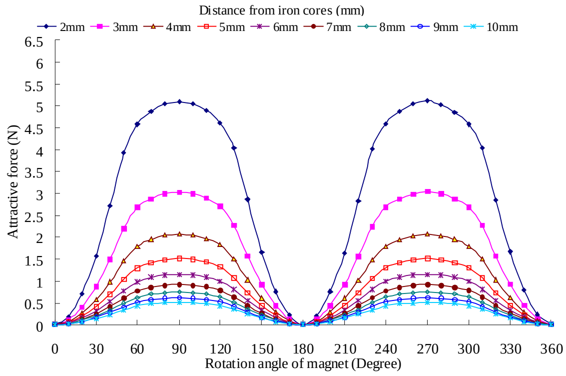

Fig.11 Experimental result of attractive force using the extending iron cores

small, and the force variations become inconspicuous from 60 to 120 degrees and from 240 to 300 degrees. And the weak variation of force causes the system uncontrolled in those areas. However, the semi-zero attractive force at 0 and 180 degrees becomes almost zero.

4.4 Comparison of Zero Attractive Force Performance

In order to evaluate the three improvement methods, the measurement attractive forces are compared with the original mechanism when the magnet stops at 0 degree. The comparison results are shown in Fig.12. From the results, we can see that, the zero attractive forces of the improvement methods are smaller than the results of original mechanism. Therefore, all the improvement methods are available. The improvement effect using the special permanent magnet is conspicuous, and is better than the inserting ferromagnetic board method. The improvement effect using extending iron cores is

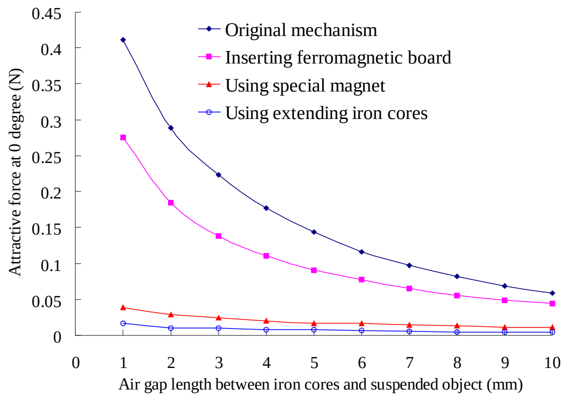

Fig.12 Comparison of all improvement methods

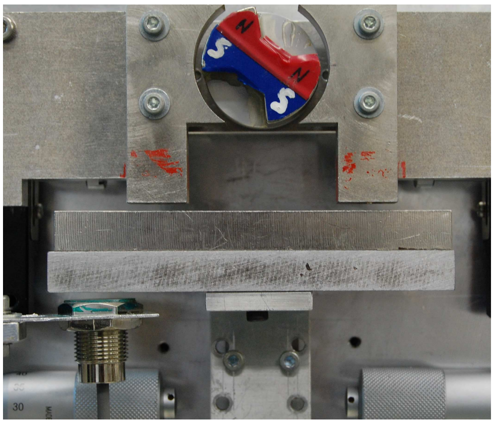

Fig.13 Photograph of suspension experiment using the special magnet

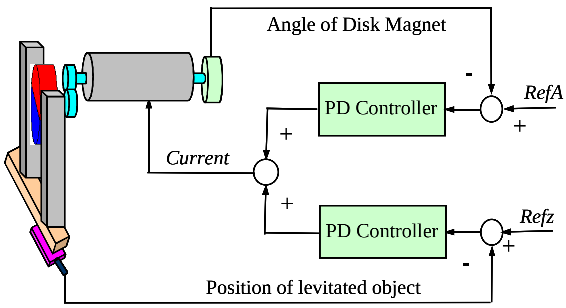

Fig.14 Control system for suspension experiment

best, but the maximum force becomes small, and the force variations become inconspicuous around the maximum forces. Therefore, the improvement method using the special permanent magnet is best through considering the zero suspension force and controllability of the mechanism.

5. Suspension Experiment Using Special Magnet

In order to examine the suspension feasibility of the mechanism using the special magnet, the suspension

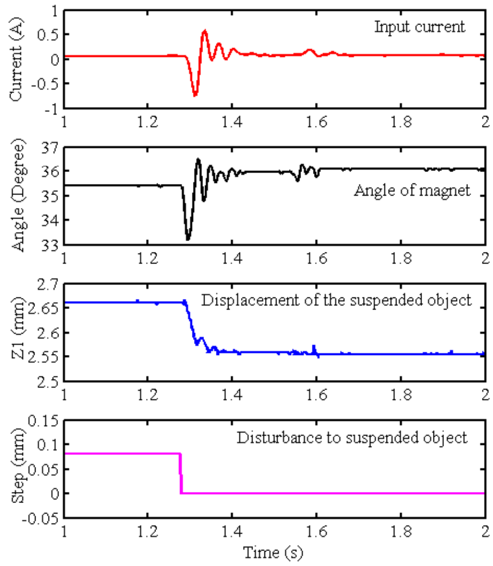

Fig.15 Step response results of suspension experiment using special magnet

experiment was carried out. The photograph of suspension experiment is shown in Fig.13.

5.1 Control System

The structure of the control system is shown in Fig.14. In this control system, two PD controllers are used. Basing on the feedback signals of the encoder and the eddy current sensor, the input current of the motor is calculated, and the suspension force is controlled.

Using LQR method, the feedback gain of this PD control system was calculated. The feedback gain K is shown as followings.

$$K = [177250 \quad 2208 \quad 391.23 \quad 1.31]$$

5.2 Suspension experiment results

Using the experimental prototype and calculated feedback gain, the suspension experiment was succeeded.

Fig.15 shows the step response results when the mass of suspended object is 0.232 kg, and the step input is 0.08 mm. In the figures, the input current, the rotational angle of magnet, the displacement of suspended object, and the disturbance are recorded from 1 second to 2 seconds. The results indicate that the suspended object can be suspended stably and the input current is almost zero at the stable state.

The results indicate that the magnetic suspension system using a special type magnet not only can improve the zero attractive force performance, but also can realize the stable suspension as the original mechanism has realized.

6. Conclusions and Future Works

6.1 Conclusions

This paper focused on the improvement of the zero suspension force of the proposed magnetic suspension mechanism, and proposed three improvement methods, which are inserting ferromagnetic board method, using special magnet method, and using extending iron cores method. The performance of the mechanism using each improvement method was examined by the measurement experiments. All the results indicated that, every method could improve the zero suspension force characteristics. However, using the method of the special type magnet or the extended iron cores could obtain the obvious improvement. Moreover, using the extended iron cores, the zero suspension force characteristics were improved, but the controllable range of the attractive force becomes narrow. Using the special permanent magnet method, the zero attractive force characteristics were improved, basing on no reduction of the controllable range of the attractive force.

In addition, the suspension examinations were also carried out with the improved mechanism using the special type permanent magnet in numerical simulation and the experiment. The results indicated that the improved mechanism also could suspend the suspended object stable.

6.2 Future Works

As the future works, using the zero suspension force characteristics, the control method of the floating off from the adhered position will be proposed, and the floating off experiment will also be carried out.

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