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A simple levitation system using wireless power supply system and Lorentz force

Koichi Oka and Masako Tanaka

Miyanokuchi 185, Tosayamada-cho, Kami-city, Kochi, 782-8502, JP

E-mail: oka.koichi@kochi-tech.ac.jp

Abstract. A new type of magnetic levitation mechanism has been proposed. The feature of this mechanism is using wireless power supply system and Lorentz forces for levitation. The stability of levitation is performed by passive control by magnetic flux configuration between permanent magnets and active control of electromagnets. In this paper, the concept of levitation mechanism is introduced, FEM analyses for levitation force and wireless power supply performance is examined. In concept two types of levitation systems which are different on the point of active control directions are introduced. In FEM analyses, the required current for levitation and the directions of generating forces are calculated. In the study of wireless power supply system, the required voltage for the levitation is expected. Finally the feasibility of the proposed levitation system will be verified.

1. Introduction

Magnetic suspension is a technology for supporting or manipulating objects without mechanical contact by means of magnetic forces. As no mechanical contacts, magnetic suspension systems have many advantages of no friction, no dirt, lubrication free, and maintenance free. Using these advantages, many magnetic suspension mechanisms have been proposed[1]. In these suspension mechanisms, electromagnetic suspension systems are widely used that control the coil currents of the electromagnets for suspension forces. Recently, however, various types of magnetic suspension systems have been developed [2][3].

The authors have previously reported a bearingless motor with rectified circuit coil of half wave rectification type[4][5]. In this type, to acquire large magnetic force of rotor, magnetic saturation of rotor and stater core will occur. In order to solve this problem, we propose a method of wireless power transmission for rotor by full wave rectification type and an inclination of teeth of stater and rotor.

In this paper, we are aiming to develop a simple magnetic levitation system and propose a new type of a magnetic levitation system. We use Lorentz force and wireless power transmission mechanism for non-contact levitation. First, concept of the levitation system and a prototype levitation system are introduced. And for the feasibility study, we verify the performance of the wireless power transmission by analyses and experiments.

2. Proposed magnetic levitation system

2.1. Prototype system

An illustration of the proposed magnetic levitation system is shown in Figure 1 and a photo of the prototype device is shown in Figure 2. The levitation mechanism is composed of a transmitting coil, a receiving coil, permanent magnets, electromagnets, and a oscillation and rectified circuits as shown in the figure. Circuits is not indicated in the figure. The receiving coil and circuits levitate without mechanical contact. Transmitting coil is connected to a capacitor for oscillation and a power supply. Transmitting coil and receiving coil have same resonance frequency and the power supply drives the frequency.

Electrical power is transmitted by magnetic resonance and the induced current is rectified to direct current of the levitation coil. The circular levitation coil is levitated by Lorentz forces generated by the current and magnetic flux of permanent magnets arranged on both sides of the coil.

The levitation coil use copper wire (UEW) with diameter 0.5[mm]. The shape is circle with 170[mm] diameter and has 50 turns. The weight is 97.1[g] and resistance is 5.9[Ω]. Transmitting and receiving coils use litz wire (7× 0.3[mm]) and spider web coil and it has 50 turns. The weight is 44.1[g].

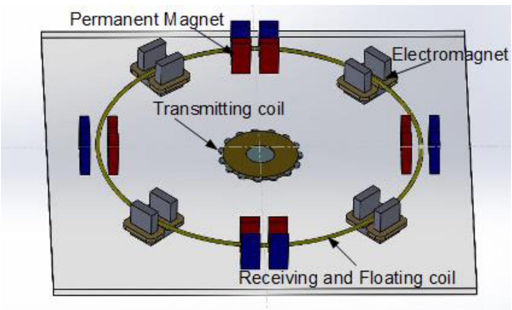

Figure 1. Illustration of proposed magnetic levitation system.

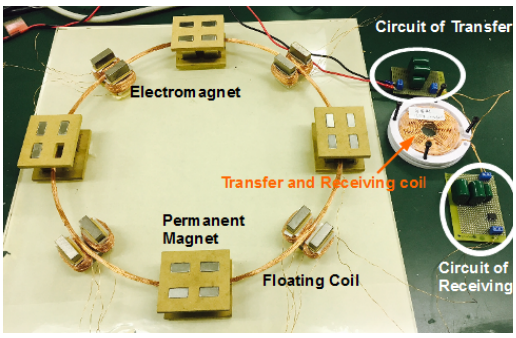

Figure 2. Photograph of prototype proposed system.

2.2. Stability of levitation

Magnetic flux around two permanent magnets which installed on the both side of the levitated coil is illustrated in Figure 3. As the direction of Lorentz force is orthogonal to the direction of flux and current, the directions of flux and force is represented as Figure 4. In the figure, ”B” indicates the direction of flux, ”F” indicates the direction of force, coaxial circles is current flow in the coil.

As shown in the figure, if the coil current is located in the center of two magnets, the direction of the force is vertical. The force strength is almost equal during the coil current is located between two magnets and it becomes smaller when the coil is upper or lower from the magnets. It means that the motion of coil displacement is stable at the upper of the magnets and it is unstable at the lower.

If the coil current moves to the left as shown in the left of the figure, in the upper the Lorentz force acts to the left and in the lower the force acts to the right. If the coil moves to the right, in the upper the force acts to the right and in the lower the force acts to the left. Consequently at the upper location the left displacement of the coil generates the leftward force, and the right displacement generates the rightward force. It means that at the upper location the horizontal motion of the coil displacement is unstable, and the lower location the horizontal motion is stable.

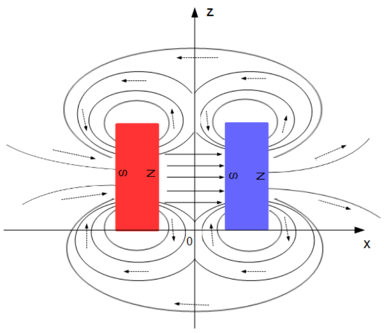

Figure 3. Flux illustration of two permanent magnets.

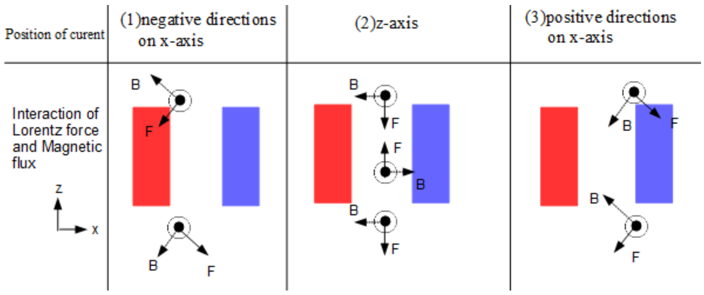

Figure 4. Force and flux direction in various points around two permanent magnets.

For unstable motion the closed loop feedback control is necessary using electromagnets shown in Figure 5. For vertical motion control the arrangement of electromagnet shown in the left of the figure can be used, and for horizontal control the right arrangement can be used.

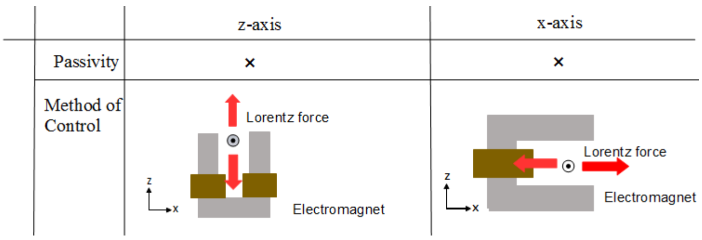

Figure 5. Direction of control force by arrangement of electromagnet.

In this paper as a first step of this research the feasibility study is investigated about estimation of the Lorentz force and performance of the transmitting power supply.

3. Estimation of Lorentz force

The proposed system uses Lorentz force for supporting and controlling the levitated object. However Lorentz force is smaller than electromagnetic force. We estimate Lorentz force whether the strength is enough for levitation using permanent magnets and control using electromagnets.

3.1. Magnetic flux around permanent magnets

Magnetic flux distribution of two faced permanent magnets has been examined for the stability check as shown in Figure 4. We use FEMM[6] analysis software and calculate the relationship between distribution and thickness of magnets. The material of the magnet is neodymium and the height is 40[mm]. The thickness alters from 10[mm] to 60[mm].

The results of 2D analyses are shown in Figure 6. As shown in the figure the flux density between two magnets is very high and almost same. At he upper and lower parts it become lower. The other parts is almost same as Figure 3. The thickness of the magnets may affect the range of the stabilized area and restoring force strength.

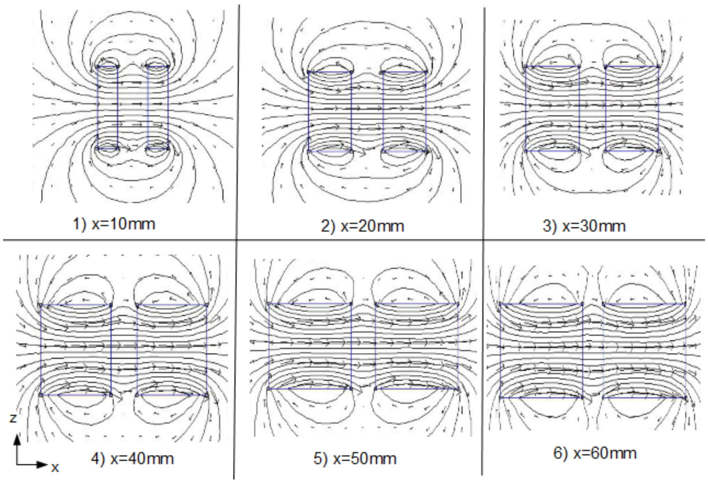

Figure 6. Flux distribution of various thickness permanent magnets by numerical simulation.

3.2. Lorentz force by permanent magnet

FEM analyses have been carried out for levitation force. We used JMAG[7] for analyses. The model of analyses is shown in Figure 7 and analyses area is shown in Figure 8. The shape of the magnet is same as a prototype. The current flowing in a wire copper is assumed as 1[A] and totally 50[A]. The analyses area is restricted as shown in Figure 8.

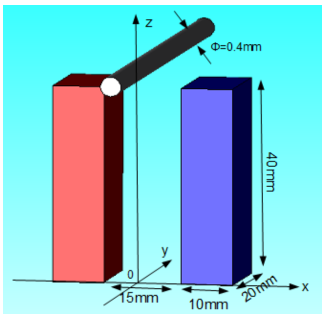

Figure 7. FEM analysis model of coil current and permanent magnets.

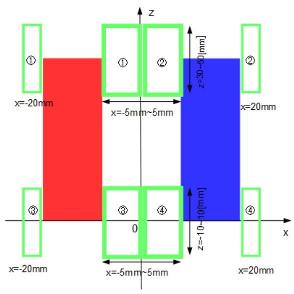

Figure 8. Calculation area of FEM analysis.

The results in the area 1 and 3 are shown in Figure 9 and 10. The results shows the relationship between vertical position of the coil and vertical Lorentz force as parameters of the horizontal position. The red line in the figure indicates the weight force of the levitation object.

The intersection of result lines and red line is the equilibrium point to levitate. It can be seen that the equilibrium positions are almost upper or lower edge of the permanent magnets. Consequently the coil current of 1[A] is enough for levitation.

As shown in the figures in area 1 the motion in the vertical direction can be seen as stable, because the result lines across the red line downward to the right. In area 3 the motion is unstable, because the result lines across upward.

The vector representation results are shown in Figure 11 and 12. Figure 11 shows the upper part and Figure 12 shows the lower part. As shown in Figure 11 arrows between magnets face to the outside, so in the horizontal direction the motion can be seen as unstable. From the Figure 12 the arrows face to the center in the x direction, so in the horizontal direction the motion can be assumed as stable.

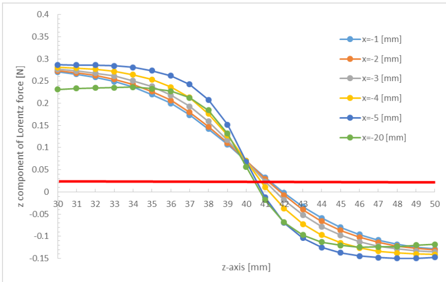

Figure 9. Relationship between vertical displacement and levitation force at upper part of permanent magnets.

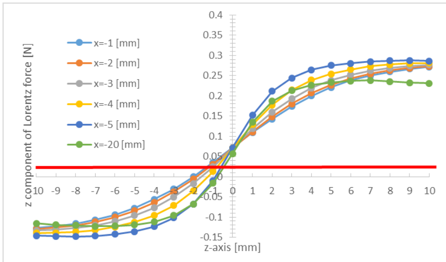

Figure 10. Relationship between vertical displacement and levitation force at lower part of permanent magnets.

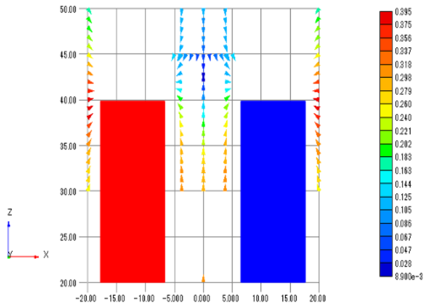

Figure 11. Direction of generating force at upper part.

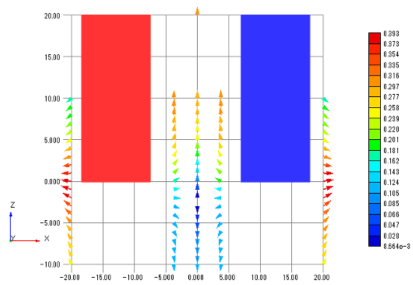

Figure 12. Direction of generating force at lower part.

3.3. Lorentz force by electromagnet

We examined the Lorentz force generated by electromagnets. The model is shown in Figure 13 and results is shown in Figure 14. The material of the magnet is SS400 and coil has 150 turns. The control currents are changed from -2[A] to 2[A]. The force, however, changes only up to 0.1[N]. This result is not enough to control force.

4. Performance of power transfer

As we aim a simple magnetic levitation system, secondary coil of power transfer should correspond to the levitation coil. As a first step, however, we use another independent secondary coil for power transfer.

The result of previous chapter indicates 1 [A] coil current is enough for levitation. So we studied the performance of power supply voltage which can provide 1[A] current for levitation coil. As the secondary coil is also levitated without mechanical contacts, the air gap between primary and secondary coil will be altered. In such a case the performance of power supply

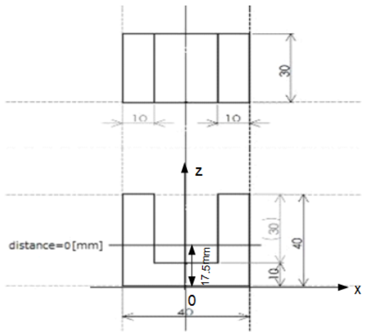

Figure 13. FEM model of electromagnet.

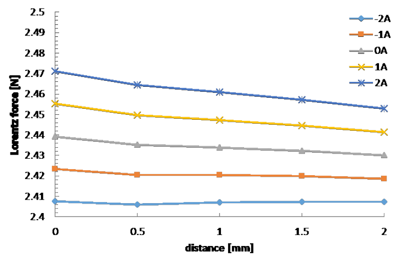

Figure 14. Levitation force including electromagnet about current and levitation position.

should be constant. We examine the different air gap performance is examined by non-contact power transfer mechanism with magnetic resonance.

4.1. Theoretical analyses

Power transfer circuit is represented as Figure 15. Primary and Secondary coil circuits are indicated. The second character of the symbol indicates the coil of primary or secondary. Each primary and secondary coil also consists of a capacitor, a register, and a inductor. Transfer mechanism uses magnetic resonance which tune the resonance frequency of both coils. R_L represents the register of the levitation coil. The circuit of Figure 15 corresponds to the T circuit as shown in Figure 16. Symbol M is mutual inductance.

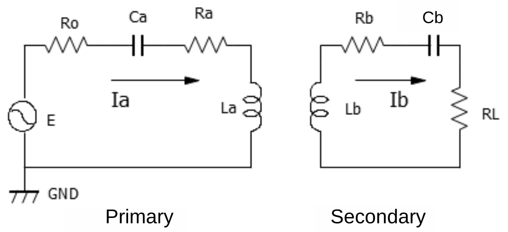

Figure 15. Primary and secondary circuit of wireless power transfer.

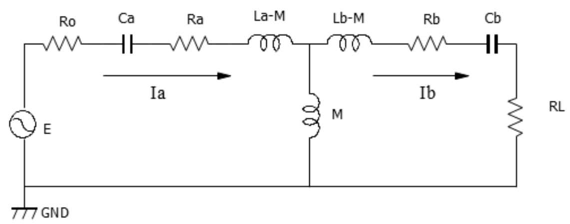

Figure 16. Equivalent T-type circuit of wireless power transfer.

We determine the resonance frequency as 10[kHz] and the air gap during levitation as from 3[mm] to 5[mm]. The characteristics of the primary and secondary coil measured by an LCR meter at 10[kHz] are as shown in Table 1. From the resonance frequency, we choose a capacitor of 2.22[μF]. Mutual inductance M and connective coefficient k are calculated as shown in Table 2

For calculation of the required voltage for the levitation coil of 1[A], we use equations as follows[8].

$$NOP = \frac{R_L k^2 \omega^2 L_a L_b}{((R_0 + R_a)(R_L + R_b) + k^2 \omega^2 L_a L_b)^2} \tag{1}$$

$$E = \sqrt{W_{RL}/NOP} \tag{2}$$

where, L_a and L_b are considered as the same values of Table 1, R_0 is same as R_a, R_L is considered as the resistance of the levitation coil and 6.0 [Ω]. W_{RL} is calculated as

$$W_{RL} = I_b^2 R_L = 1[A]^2 \times 6[\Omega] = 6 \tag{3}$$

The results of calculation is shown in Table 3. As shown in the table, we can seen a little difference of voltage for same levitation current. However the difference is very small and we may neglect.

Table 1. Power transfer coil specifications.

	Ls[μ H]	Cs[μF]	Rs[Ω]	DCR[Ω]
Primary coil (transmitting coil)	113.3	223	0.30	0.31
Secondary coil (receiving coil)	113.3	223	0.29	0.31

Table 2. Mutual inductance and connective coefficient.

air gap[mm]	mutual inductance[μH]	connective coefficient k
3	80.9	0.714
4	80.2	0.707
5	79.1	0.701

Table 3. Required voltage for 1[A] levitation coil.

air gap[mm]	R_0 [Ω]	ω [k rad/s]	R_L [Ω]	required voltage [V]
3				5.82
4	0.30	62.8	6.0	5.78
5				5.7

4.2. Experimental examination

Experimental examinations were carried out. As the result of an experiment in advance the resonance frequency is fixed as 10.353[kHz]. The currents in the levitation coil and the levitation forces are measured when the supply voltage and air gap are changing. The air gap is changed from 1[mm] to 7[mm], and the voltage is changed from 6 volts to 9 volts.

The results are shown in Table 4 and 5. The levitation coil can be levitated when the supply voltage is 8 volts and air gap is 2[mm] and 3[mm], and the supply voltage is 9 volts. Minus signs in the tables indicate that the power is over loaded.

The transferred current in experiment is about a half of the theoretical examination. It is because the loss of the rectified circuit. However the levitation coil can be levitated. The sufficient AC power supply may generate enough levitation force including the weight of a secondary coil and circuits.

Table 4. Experimental results of current of levitation coil.

air gap[mm]	6 [V]	7[V]	8[V]	9[V]
1	0.466	0.546	0.624	0.704
2	0.482	0.565	0.648	0.732
3	0.486	0.569	0.653	0.736
4	0.515	0.605	-	-
5	0.537	0.627	-	-
6	0.566	-	-	-
7	-	-	-	-

Table 5. Experimental results of levitation force.

air gap[mm]	6 [V]	7[V]	8[V]	9[V]
1	1.29	1.51	1.72	1.94
2	1.33	1.60	1.79	2.02
3	1.34	1.57	1.80	2.03
4	1.42	1.67	-	-
5	1.48	1.73	-	-
6	1.56	-	-	-
7	-	-	-	-

5. Conclusion

A new type of magnetic levitation system has been proposed. A prototype levitation system was made and the feasibility study has been carried out.

It was verified that coil current 1[A] is enough for levitation using neodymium permanent magnets. At the upper part of permanent magnets, the motion in the horizontal direction is unstable and the motion in the vertical direction is stable. Inversely at the lower part, the horizontal direction is stable and the vertical direction is unstable.

The control performance of electromagnets was not enough, so we should give some improvements such as modification of the shape of the magnet.

About the power transfer performance, it was verified the levitation coil can be levitated theoretically and by experiments. However the current of experiments was about a half of the theoretical values.

Consequently it is confirmed that the proposed magnetic levitation system is feasible.

As the further study, the control strategy should be considered. For correspondence of the secondary coil and the levitation coil, we should use a half bridge rectified circuit and it decreases the performance of power transfer. Totally we proceed to study for the complete magnetic levitation system.

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