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BEARINGLESS MOTOR WITH RECTIFIER CIRCUITS

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ABSTRACT

In this paper a new type of bearingless motor is proposed. Bearingless motors are classified as actuators whose generating mechanisms for driving and bearing force are combined. Driving generates a torque that rotates or propels, and bearing generates a supporting force for a rotor. The proposed bearingless motor will have a rotor with a rectifier circuit. The rectifier circuit will activate the rotor in a fixed direction by applying AC power. The activated rotor will be rotated as a PM stepping motor. Compared with other PM motors, there is no actual permanent magnet, so the magneto resistance in the magnetic circuits of the motor is decreased and a higher performance for the controller can be expected.

We discuss the feasibility of the proposed bearingless motor in this paper. First, we describe how the rectified rotor will be activated. Then configurations for two types of proposed bearingless motors are introduced. Finally, numerical simulations on simple model are carried out, and the feasibility of the proposed bearingless motor is determined.

INTRODUCTION

A number of developments in bearingless motors (self-bearing motors) have already taken place[1]. There are various motor types: induction motors, permanent magnet motors, switched or variable reluctance motors, and so on. Bearingless motors are defined as those having a combined bearing force and motor torque mechanism.

We proposed a novel type of bearingless motor. The primary characteristic of the proposed bearingless motor is that the rotor has a rectified circuit coil. When high frequency magnetic waves are applied to the rotor, the rotor is magnetically excited in a fixed direction because mutual induction flow in the coil current moves only in a fixed direction. Therefore the rotor can be thought of as a permanent magnet that has been installed. The rotor is driven as a PM stepping motor in rotation and its position is controlled by attractive and repulsive magnetic forces. There is no permanent magnet; the proposed bearingless motor can be expected to provide a simple, robust and maintenance-free structure.

As a first step the feasibility of the proposed bearingless motor should be studied. The principle of the rotor with rectified circuit coil needs to be explained. Next, the configuration of bearingless motors should be introduced. Then, based on the difference in direction of the flux through the rotor, two types of bearingless motors may be proposed. We explain type of motor from the perspective of the mechanism for generating force and torque. To make the feasibility more realistic, the proposed motors are modeled and simulated numerically.

PRINCIPLE OF EXCITATION OF ROTOR WITH RECTIFIED CIRCUIT COIL

Consider the illustration as shown in Figure 1 for explanation of the principle of a rotor with rectified circuit coil. The center rod in the figure is a rotor. The rotor is wound by a coil which has a diode in its circuit. The left and right side rods are stator cores which are also coil wound but driven by amplifiers. The excitation mechanism is the same as for a rectified motor [2]. The circuit equations for the illustration shown in Figure 1 are as follows:

$$v_0 = r_0 i_0 + \frac{d\Phi_0}{dt} \tag{1}$$

$$v_1 = r_1 i_1 + \frac{d\Phi_1}{dt} \tag{2}$$

$$v_2 = r_2 i_2 + \frac{d\Phi_2}{dt} \tag{3}$$

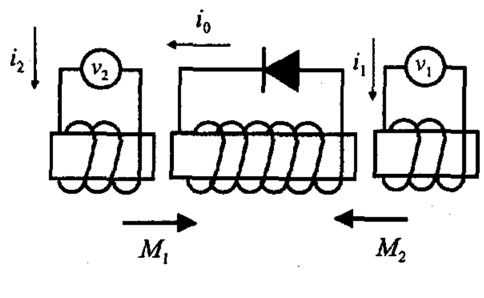

FIGURE 1: Outline of rotor with rectified circuit coil

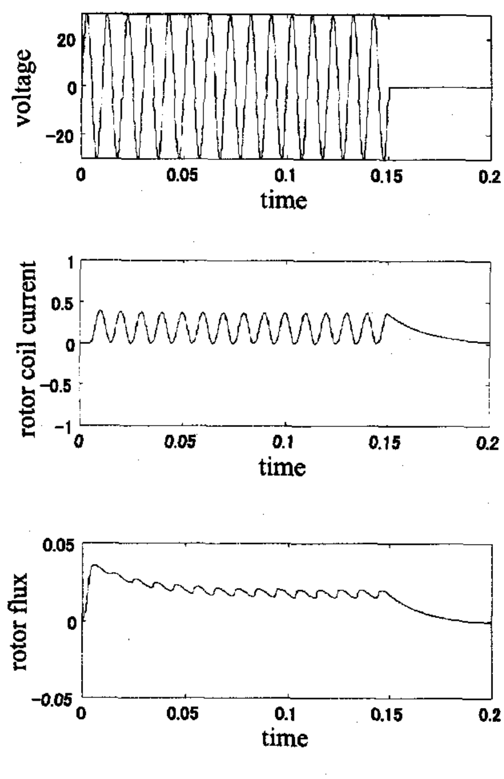

FIGURE 2: Currents and flux

where,

$$\Phi_0 = L_0 i_0 + M_1 i_1 + M_2 i_2$$
$$\Phi_1 = L_1 i_1 + M_1 i_0 + M_{12} i_2$$
$$\Phi_2 = L_2 i_2 + M_2 i_0 + M_{12} i_1$$

The symbols in the above equations are: v_0: field voltage, v_1, v_2: applied voltages for stator coils, r_1, r_1, r_2: resistances of coils, i_0, i_1, i_2: currents of coils, Φ_0, Φ_1, Φ_2: magnetic fluxes through cores, L_0, L_1, L_2: self inductances, M_1, M_2, M_{12}: mutual inductances.

When a voltage is applied to the stator coils as in

$$v_1 = v2 = A_b \sin \omega_b t \qquad (4)$$

where A_b is the amplitude of the input wave and ω is the frequency, then the current of the rotor coil and the interlinkage flux through the rotor, which have a synchronized input frequency, are derived by mutual inductance. The diode in the rotor windings is switched to OFF when the interlinkage flux of the rotor is increasing, and switched to ON so a current flows in the rotor windings to maintain existing flux when the interlinkage flux is decreasing. This operation excites the rotor just as a permanent magnet would were it installed.

The coil currents and interlinkage flux of the rotor are calculated as shown in Figure 2 with applied voltage, rotor current, and interlinkage flux given. The simulation starts when a voltage is applied. The applied voltage ceases after 0.15s. As shown in the figure, an almost fixed flux is generated at 0.1s and, after the applied voltage stops, the flux still flows for a moment.

CONFIGURATION OF BEARINGLESS MOTOR

Two configurations for the proposed bearingless motors are introduced. One is a type of bearingless motor whose rotor is excited in the radial direction. The other is one whose the rotor is excited in the axial direction.

Bearingless Motor with Radially Excited Rotor

The configuration of the bearingless motor with the rotor excited in a radial direction is schematically represented in Figure 3. There are 4 poles in the stator so that it is the same as the 4 poles in a stepping motor. Each pole has two windings. One is for excitation of the rotor and is driven in harmony with the windings on the opposite side. It is called a bias coil. A bias coil cannot be driven independently. As bias coil 1 and bias coil 3 have a serial connection, they are operated according to the following current

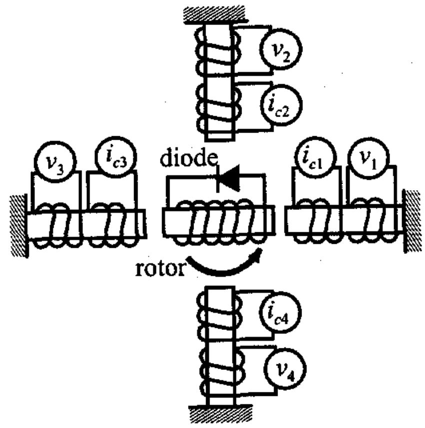

FIGURE 3: Schematic illustration of bearingless motor I (radially excited rotor type)

calculations.

$$i_{1b} = i_{3b} \tag{5}$$

$$i_{2b} = i_{4b} \tag{6}$$

where, i_{1b}, - i_{4b} are the currents of bias coils.
The other winding is for position control in the axial direction and for generating the torque for the motor. It is called a control coil. The control coil currents can be controlled independently.
When the rotor angle is located as shown in Figure 3, the horizontal position and the rotation of the rotor may be actively controlled by adjusting the currents of the control coils for the left and right poles while the vertical position is stabilized without active control. Therefore the rotor can be levitated without mechanical contacts and will rotate accordingly.
Now we assume that the rotor is excited by using the rectified coil on the left side of the rotor as the N pole. Thus means that a magnetic flux flows from the right pole(S) to left pole(N). A leftward propulsive force created by excitation of the left control coil to strengthen the flux and the right control coil to weaken it, can be generated. Similarly a clockwise torque created by excitation of the control coils of both the upper and lower stator poles can be generated to derive an upward flux.

Bearingless Motor with Axially Excited Rotor

The second type of bearingless motor with rectified circuit coil has the rotor excited in the axial direction. A basic configuration is illustrated as Figure 4. The chief characteristic of this bearingless motor is that excitation by the rectified circuit coil is made in the axial direction.
There are two radial bearings which are on the left and right side. A side view of the radial bearing on one side is shown on the right. A radial bearing has 6 poles on the stator. The rotor itself is shaped like an H. Magnetic flux flows in the rotor from one side to the other side of a stator pole.

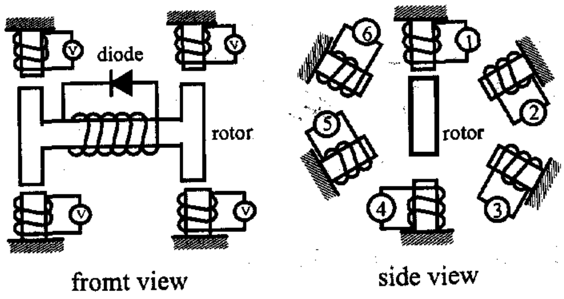

FIGURE 4: Schematic illustration of bearingless motor II (axially excited rotor type)

Four bias coils are connected in series and operated by a amplifier. The relationship between currents of bias coils are calculated as follows:

$$i_{l1} = i_{l4} = -i_{r1} = -i_{r4} \tag{7}$$

$$i_{l2} = i_{l5} = -i_{r2} = -i_{r5} \tag{8}$$

$$i_{l3} = i_{l6} = -i_{r3} = -i_{r6} \tag{9}$$

Control coil currents are individually adjusted and all degrees of freedom of the rotor except thrust direction are actively controlled.
An assumption is made that the rotor stays in place as in Figure 4. Then one side of the radial bearing where flux flows from rotor to stator is examined. Position control in the vertical direction is created by the excitation of coils 1 and 4. Upward flux of coil 1 and downward flux of coil 4 generate a force in an upward direction. Position control in the horizontal direction and rotation control are created by the excitation of coils 2, 3, 5, and 6. Rightward horizontal force is generated by exciting the outward flux of coils 2 and 3 and the inward flux of coils 5 and 6. Clockwise torque is generated by exciting the outward flux of coils 2 and 5 and the inward flux of coils 3 and 6.
Thus we can actively control 3 directional vectors on one side of the radial bearings. So both side bearings are able to control five degrees of freedom of the rotor.

NUMERICAL SIMULATION

To make the feasibility study more convincing, numerical simulations are carried out. A motor with a radially excited rotor with a rectified circuit is examined, when the rotor stays in phase and when it changes from one phase to the next. Here we assume that the gravitational force is negligible. Thus can be

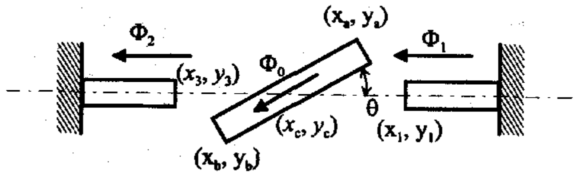

FIGURE 5: Symbols for representation of motion

realized by setting the face of Figure 3 to horizontal.

Simulation with Rotor in Phase

When the motion of the rotor of a bearingless motor is examined, circuit equations take the movement of the rotor into account. In the case of the rotor staying in phase, only two poles of the stator affect the movement of the rotor. The symbols for their motion are shown in Figure 5. In the figure, the coil is omitted for the sake of simplification. The symbols in the figure are: x_1, y_1, x_3, y_3 are positions of the stator poles, x_a, y_a, x_b, y_b are positions of the rotor tips, x_c, y_c are positions of the center of the rotor, θ is the angle of the rotor ω is the angular velocity of the rotor. The point of origin for the center of the stator pole is set.

The circuit equations are changed from (1)-(3) to

$$v_0 = r_0 i_0 + \frac{d\Phi_0}{dt} + \frac{dl_1}{dt}\Phi_0 + \frac{dl_2}{dt}\Phi_0 \qquad (10)$$

$$v_1 = r_1 i_1 + \frac{d\Phi_1}{dt} - \frac{dl_1}{dt}\Phi_1 \qquad (11)$$

$$v_2 = r_2 i_2 + \frac{d\Phi_2}{dt} - \frac{dl_2}{dt}\Phi_2 \qquad (12)$$

where,

$$l_1 = \sqrt{(x_1 - x_a)^2 + (y_1 - y_a)^2}$$
$$l_2 = \sqrt{(x_2 - x_b)^2 + (y_2 - y_b)^2}$$

The forces acting on the rotor are

$$f_a = \Phi_0 i_1 \qquad (13)$$

$$f_b = \Phi_0 i_2 \qquad (14)$$

where, f_a is the force acting on the right tip of the rotor and f_b is the force on the left. Mutual inductances are varied according to the air gap between the rotor and the stator. A smaller air gap creates a larger mutual inductance. That the mutual inductances are represented by a single order of the air gap is assumed.

Active control is only in the horizontal direction. Variation of the control coil current causes the variation of the bias coil current. The following control strategy is proposed for levitation of the rotor.

$$i_c = -k_p x_c \qquad (15)$$

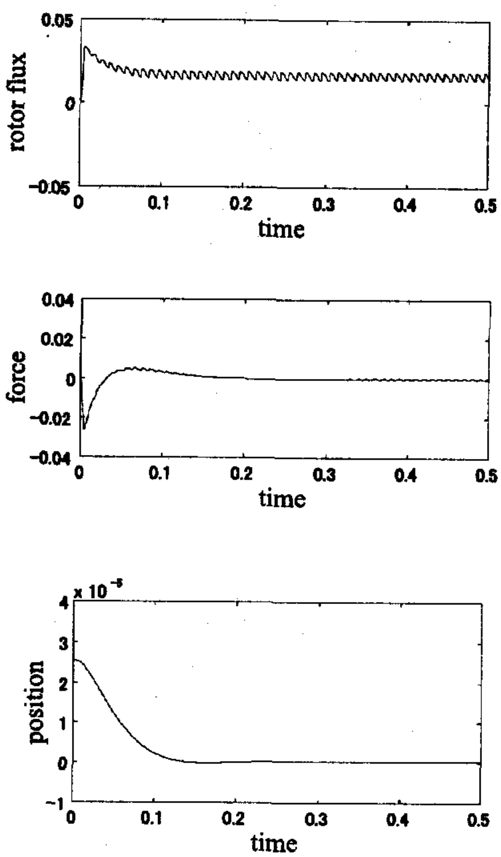

FIGURE 6: simulation result when the rotor stays in a phase

Simulation results are shown in Figure 6 which illustrates movement in the horizontal direction. In the initial state, there is an error of position of the rotor 2.5e-5 [mm]. The linkage flux through the rotor, the force acting on the rotor, and the position are recorded. As shown in the Figure, there are small vibrations in both flux and force. As for the position, however, we cannot see such a vibration.

Consequently adjustment of the control coil currents can control the rotor and feasibility of the proposed bearingless motor is supported by this simulation.

Simulation at Changing Phase

Next, the rotation of the rotor is considered. It is assumed that the linkage flux of the rotor Φ_0 is fixed during operation. The rotor angle is defined for a horizontal position of zero and a counterclockwise directional rotation is called plus. The rotor is first set to $-\pi/3$. Stator coils 1 and 3 become active and the rotor diverges to the angle 0. During divergence,

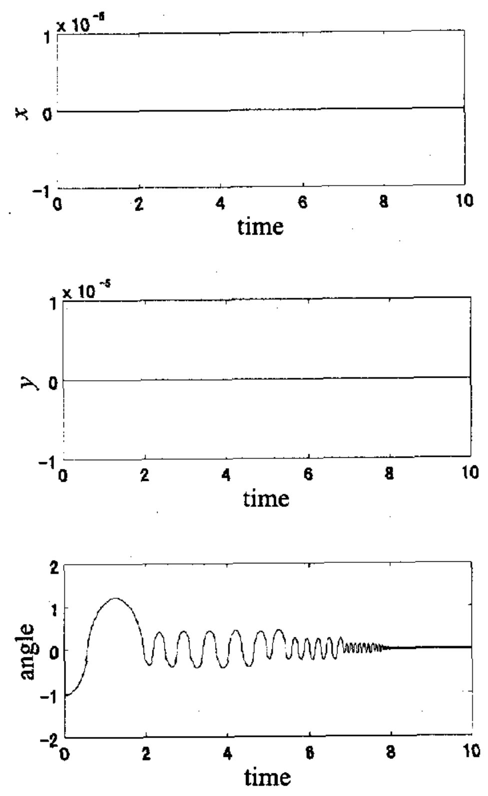

FIGURE 7: simulation result when the rotor rotate (change phase)

x and y position and the rotor angle are calculated. Results are shown in Figure 7. These results show that rotation of the rotor does not affect the movement of x and y. However, this simulation is set at 0 about x and y position in the initial state. Another simulation which had slight deviation in the initial x position did not succeed. Therefore, we may conclude that during the rotation of the rotor, control of x and y direction may be necessary.

CONCLUSION

To conclude a novel bearingless motor which has a rotor with a rectified circuit has been proposed in the paper. Two types of configuration of bearingless motors have been introduced and operation methods have been explained. Numerical simulations for the feasibility study have been done that verify the performance of this motor. However the numerical simulations have been carried out in an ideal state. There will be many difficulties to realize success for the proposed bearingless motor in a natural state. Problems such as inequality of the stator pole characteristics, the robustness of levitation, the control method for the rotor must be solved. Further studies involving basic experimental examinations of the rotor variables with the rectified circuit coil will be on going.

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References

1. A.O. Salazar, A. Chiba, and T. Fukao, A Review of Developments in Bearingless Motors, Proc. of the 7th Int. Simp. on Magnetic Bearingss, pp.335-340, 2000
2. J. Oyama, T. Abe, T. Higuchi, E. Yamada, and K. Shibahara, Sensor-less Control of a Half-Wave Rectified Brushless Synchronous Motor, Conference Record of the 1995 IEEE Industry Applications Society Annual Meeting, Vol. 1, pp.69-74, 1995