THE EXPERIMENTAL RESULT OF A BEARINGLESS PERMANENT MAGNET DISK-TYPE MOTOR

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ABSTRACT

The bearingless motor needs composing of some complex assemblies. Especially, some controller devices of two kinds of winding which consists of a bearingless motor are very complex. The bearingless permanent magnet disk-type motor consists of only armature winding. A simple bearingless motor composed of an axial-gap disk-type motor and only one pair of cylindrical form permanent magnets is suggested.

INTRODUCTION

There are many heart failure patients all over the world. In case of serious condition, these patients need the heart transplant. However, a paucity of donor hearts and tremendous costs are limiting these factors to heart transplants. Because an artificial blood pump requires alternative to transplants. A magnetically suspended centrifugal pump using the bearingless motor technology has feature of slight wear, no maintenance of pump because the bearingless motor do not use mechanical bearings, which discourages blood thromboembolism. Therefore, it is expectable as substitution of the long-term artificial heart. This is the reason why many studies have been conducted on the bearingless motors, which are the magnetic bearing adopted motors [1],[2].

The bearingless motor usually needs composition of many complex assemblies, large mechanism, and complicated control system. This bearingless permanent magnet disk-type motor is one of bearingless motor which solve these problems. A simple bearingless motor composed of an axial-gap disk motor and only one pair of cylindrical form permanent magnets are suggested. Disk-type motor makes better use of magnetic flux exist in the gap, because the torque and attractive force can be controlled at the same time.

In this paper, the characteristic of the disk-type motor, the characteristics of the magnetic bearing, and the characteristic which mixed them, that is the characteristic of bearingless motor are described. The experimental results of the proposed motor is described.

BEARINGLESS MOTOR

CONSTRUCTION OF THE BEARINGLESS MOTOR

The bearing system which composed of a pair of cylindrical permanent magnets is suggested. Fig.1 shows a simple bearingless motor composed of an axial-gap disk motor and only one pair of cylindrical form permanent magnets. The radial stiffness should be considerably higher in this case, because otherwise the unsymmetrical force generated by the disk motor spoils the advantage that the system has passive stability in radial direction. If Earnshaw's theorem is taken into consideration, stable levitation can be realized with controlling only the attractive force of the motor. And this system decreases some controlling systems and equipments. The repulsion force of a pair of cylindrical permanent magnetic bearing is calculated. As the result of the calculation, it appears that certain region surely exists that has negative stiffness. Therefore, the disk-type motor has the special feature of being simple.

Fig.2 shows the relation of the rotary torque and the attractive force on the disk-type motor. It shows the principal of controlling motor. Accordingly, it is possible to control the rotary torque and the attractive force separately at the same time as shown in a figure. The following paragraph describes the control system.

In this paper, the confirmation of the possibility of magnetic levitation and rotation is described. The experiments divide into the magnetic bearing and the disk-type motor, and their characteristics are examined.

THE CONTROL SYSTEM OF THE BEARINGLESS MOTOR

The control system of the bearingless motor is considered. The kinetic equation of the rotor is shown in an equation (1). The expression of relations of the attractive force F is shown in an equation (2). It is assumed that they are ideal conditions. Therefore, the disk-type motor does not exist the leakage flux and a hysteresis in the stator, and the iron core dose not have the magnetic saturation and the effect of an eddy current. The relation between the repulsive force and a gap is shown in an equation (3).

The attractive force of the bearingless motor is nonlinear. In order to apply the linear control theory, this linearization is required. An equation (1) is transformed into an equation (4) by equations (2) and (3). Moreover, a rotation equation and a voltage equation are shown in equations (5) and (6). And the block diagram for controlled object is shown in Fig.3.

$$m\ddot{z} = -f_m - f_{pm} - a\dot{z} + f_b(z) + f \qquad (1)$$

m: Mass of the rotor [kg], z: Gap [mm], f_m: Attractive force of the disk-type motor [N], a: Viscosity coefficient of the fluid [Ns/m], $f_b(z)$: Repulsive force of the magnetic bearing [N], f: External force [N], f_{pm}: Force in which a permanent magnet attracts the rotor [N]

$$F = Y\left(\frac{i_m}{z}\right)^2 \qquad (2)$$

i_m: Excitation current [A],
Y: Coefficient of the attractive force [Nm^2/A^2]

$$f_b(z) = bz \qquad (3)$$

$$m\ddot{z} = \left(\frac{2YI_m^{\,2}}{Z^3}\right)z - \left(\frac{2YI_m}{Z^2}\right)i_m - a\dot{z} + bz - f \qquad (4)$$

$$\frac{1}{2}mr^2\frac{d^2\theta}{dt^2} = \tau_m + \tau_d \qquad (5)$$

r: Radius of the rotor [m], θ: Rotation angle [deg],
τ_m: Rotation torque [Nm], τ_d: Load torque [Nm], b: Elastic coefficient [N/m]

$$e = Ri_m + L\frac{d\,i_m}{dt} + K\frac{d\theta}{dt} \qquad (6)$$

R: Resistance [Ω], e: Applied voltage [V], L: Inductance [H], K: Coefficient of the back electromotive force

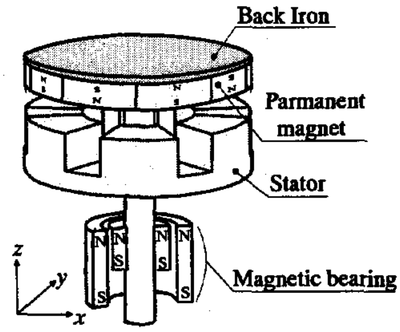

FIGURE 1: A simple bearingless motor composes of an axial-gap disk-type motor and only one pair of cylindrical form permanent magnets.

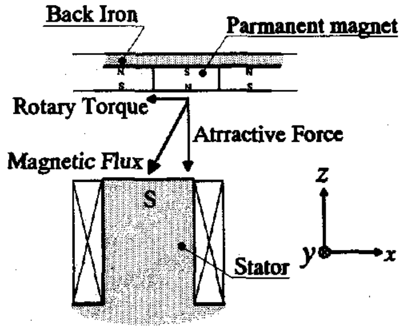

FIGURE 2: The relation of the rotary torque and the attractive force on the disk-type motor.

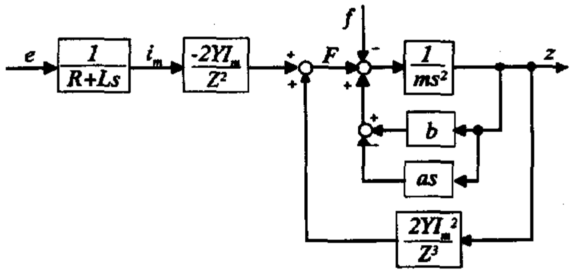

FIGURE 3: The block diagram for controlled object.

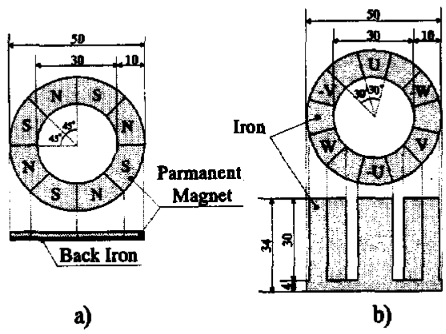

FIGURE 4: The assemblies of the disk-type motor:
a) The Rotor, b) The Iron Stator.

THE CHARACTERISTICS OF THE DISK-TYPE MOTOR

The disk-type motor is 3-phases PM-type synchronous motor. Fig.4 shows the assemblies of the disk-type motor of the rotor and the stator.

In order to grasp the characteristics of motor rotation and an attractive force, we calculated and measured the characteristics with the experimental device for the rotary characteristics. In case of control, the problem that we have to consider is the attractive force fluctuation improvement in the motor structure, we experiment two kinds of rotor having 4 and 8 magnetic poles with 6 magnetic poles stator. And the input is 3-phase AC from a PWM amplifier per phase. Fig.5 shows the experimental device. A device has torque meter, a rotary encoder, and a powder brake on the same axis of the rotor. And because the stator is on a linear guide, it can be freely moved in the right-and-left direction of a figure. For that reason, the attractive force can be measured using the load cell in which it was attached by the plinth of stator. The computer takes in all measured value.

The torque and the attractive force were measured by experimental device. Fig.6 [4] shows the characteristic of the attractive force when the load is kept at 0.05 Nm, then number of rotation per minute are 900 rpm and 1500 rpm. An attractive force has decided on the power angle. Number of motor rotations per minute is to 1800 rpm, because the emf is proportion to the rotations.

Then it seems that the control range is narrow. The value of the control range is 5 N. And when the responsibility is expressed with dF/dI, the value is 5 N/A. Therefore, the control of the attractive force may become delicate. In the following paragraph, the mock experiment of levitation is described.

PERMANENT MAGNETIC BEARINGLESS SYSTEM

The bearing system is composing of a pair of cylindrical hollow permanent magnets[3]. These two permanent magnets are placed on the same axis as shown in Fig.7. In this case, the following conditions need to be satisfied for functioning as the magnetic bearing.

$$Kr = \frac{\partial Fr}{\partial r} < 0 \tag{7}$$

$$Kz = \frac{\partial Fz}{\partial Z} < 0 \tag{8}$$

$$K\phi r = \frac{\partial F\phi r}{\partial \phi r} < 0 \tag{9}$$

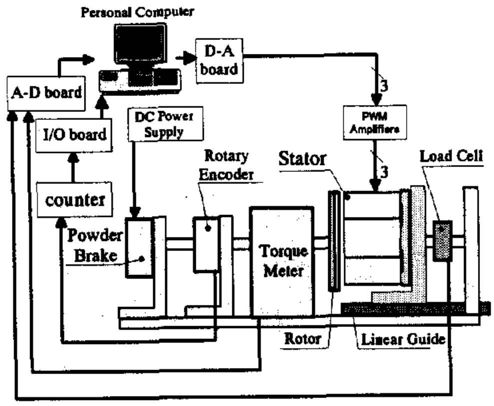

FIGURE 5: The experimental device for the rotary characteristics.

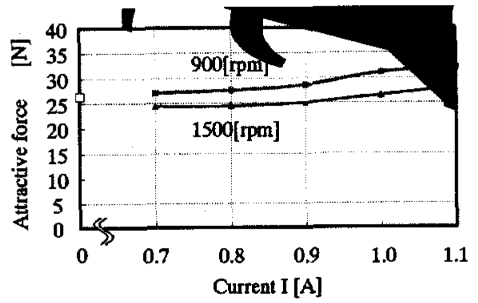

FIGURE 6: The characteristics of the attractive force when the load is kept at 0.05 Nm, then number of rotation per second are 900 rpm and 1500rpm.

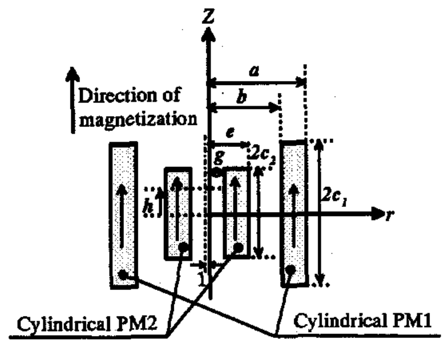

FIGURE 7: The position of the bearing system composed of PM1 and PM2 when shifting a PM2 up.

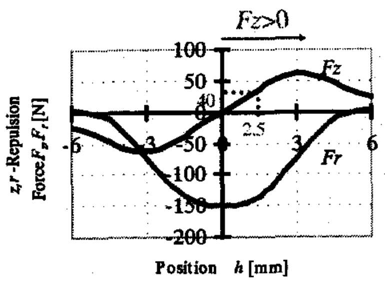

FIGURE 8: The characteristic between position h and the repulsion force of the direction of z, r axis (Fz, Fr) when shifting a PM2 up.

Kr, Kz, Kφr: Stiffness of the direction of *r*, *z*, and *φr* axis, *Fr, Fz, Fφr*: Force of the direction of *r*, *z*, and *φr* axis

The characteristic of the permanent magnetic bearing system was measured by experiments. The position of the bearing system between the permanent magnet 1 (PM1) and the permanent magnet 2 (PM2) are shown in Fig.7. The experiment was conducted by fixing PM1 and moving PM2. Fig.8 shows the characteristics between position *h* and the repulsion force of the direction of *z*, *r* axis (*Fz*, *Fr*) when shifting a permanent magnet 2 up, where values of each part were set to a=24, b=14, $2c_1$=12, $2c_2$=6, e=11, g=1 mm. The attractive force of disk-type motor is 40 N because F_z must be positive.

It proves that the repulsive force balances with the attractive force of the disk-type motor in the position, which shifted PM2 from the center to 2.5mm above.

Next time, the characteristics when changing the height of PM2 ($2c_2$) was measured by experiment. The position measured from the place with which the same bottom end of PM1 and PM2. The relation of the position of PM1 and PM2 is shown in Fig.9. And Fig.10. shows the measurement results of *Fz* and *Fr*. Value except $2c_2$ has not changed at this time. The saturation of *Fr* has happened, when the cross-section area of PM1 and PM2 becomes the same. And, it balances with the attractive force of a disk-type motor at the time of $2c_2$= 15 mm.

As their results of measurement, it turns out that attractive force and repulsion force balance with each other. The realization of the permanent magnet type magnetic bearing becomes definite.

THE EXPERIMENTS OF THE MOCK MAGNETIC LEVITATION

The magnetic levitating experiment was conducted in order to check the realization of levitating the bearingless permanent magnet disk-type motor. The experiment of the mock magnetic levitation was conducted at the time of no rotation and rotation at 1000rpm.

THE MOCK MAGNETIC LEVITATION BY MEANS OF THE SPRINGS AT THE CASE OF NO-ROTATION

Two kinds of experiments were conducted. One is the experiment which mocked the magnetic bearing by means of a spring. Fig.11 shows the experimental device for the magnetic levitation on the disk-type motor. The flexibility is given only in the direction of Z-axis. Gravity is not taken into consideration for the experiment device. The magnetic

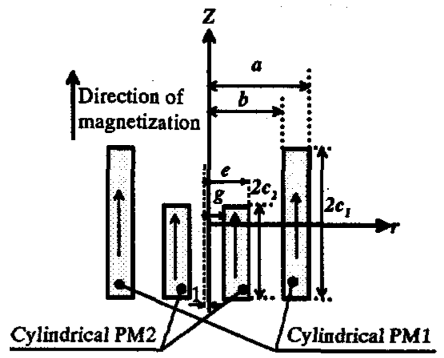

FIGURE 9: The position of the bearing system composed of PM1 and PM2 when the height of PM2 is changed.

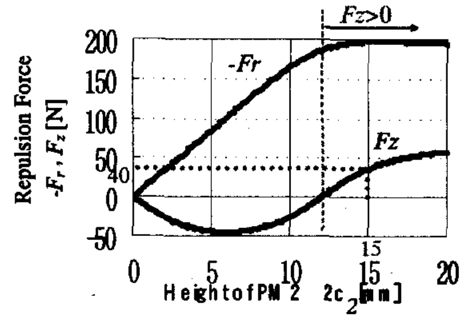

FIGURE 10: The results of measurement of *Fz* and *Fr* when the height of PM2 is changed.

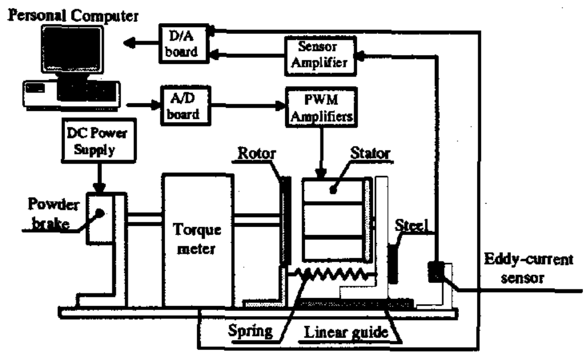

FIGURE 11: The experimental device for the mock magnetic levitation by means of springs.

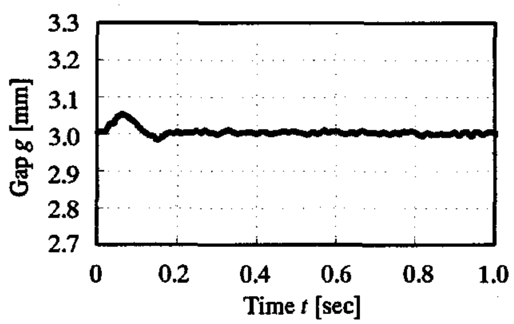

FIGURE 12: The experiment result of mock levitation on the disk-type motor.

bearing was imitated by means of a spring. The sensor gauges a gap. The motor controller has the PID control with the current minor loop. The gap is measured by the eddy-current sensor.

Fig.12 is a result of a magnetic levitating experiment on the disk-type motor when the gap command value is 3 mm and no rotation condition. According to the Fig.12, the disk-type motor is controlled as order value. The experiments showed that the rotor can levitate magnetically.

Fig.13 shows balanced levitating range in the part of resultant force between the attractive force of the disk-type motor and the repulsion force of the spring. The place where the resultant force become 0 N with the spring which imitated the magnetic bearing is balanced position. The force is measured by making change from 0 A to maximum 1.2 A. 2.9 mm to 3.3 mm are balanced the range of levitation. Accordingly, balanced levitating range is 0.4mm. The larger one of range is better. It is mentioned that the control range of the attractive force by current is narrow as this cause.

THE MOCK MAGNETIC LEVITATION APPLIED THE PERMANENT MAGNETS TO THE MAGNETIC BEARING

Other side is the experiment which applied the permanent magnet to the magnetic bearing. Fig.14 shows the experimental device. The flexibility is given only in the direction of Z-axis. Gravity is taken into consideration for the experiment device. The pivot bearings are set in the top and the lower ends of the device. The motor controller has the PID control with the current minor loop.

Fig.15 shows the result of experiment. The experiment of levitation which actually applied the permanent magnet to the magnetic bearing was successful, however, when having given flexibility only in the direction of Z-axis. From now on, the experiment which removed restriction of flexibility will be required.

THE MOCK MAGNETIC LEVITATION AT THE CASE OF ROTATION

The experiment of the mock magnetic levitation at the case of 1000 rpm was conducted. The disk-type motor has only the flexibility of the axial direction, and the magnetic bearing is imitated by the springs. An experiment result is shown in Fig.16 Simultaneous control of rotation and levitation was possible. However, the magnetic levitation and rotation were performed by 3.05mm to 3mm command. The experiment using the spring was successful, however, in the experiment using the permanent magnet, because the PID-gain has not

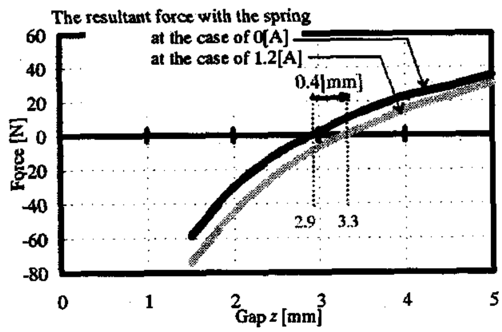

FIGURE 13: The balanced levitating range in the part of resultant force between the attractive force of the disk-type motor and the repulsion force of the spring.

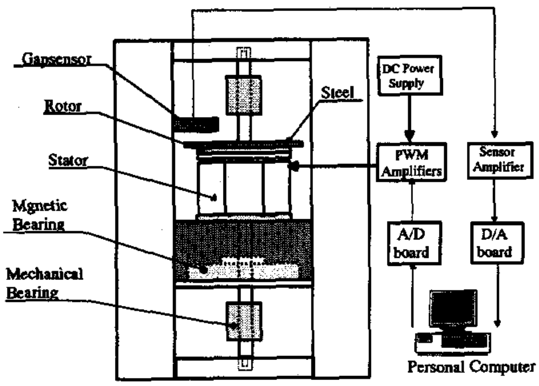

FIGURE 14: The experimental device for magnetic levitation applied the permanent magnet to the magnetic bearing.

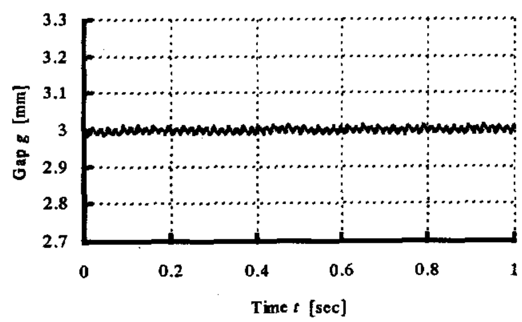

FIGURE 15: The experiment result of mock levitation applied the permanent magnet to the magnetic bearing.

been adjusted, it did not succeed. From now on, it will be dependent on adjustment of the PID-gain and could succeed in the experiment of levitation and rotation.

CONCLUSIONS

The proposed bearingless motor was divided into the magnetic bearing and the motor, the basic experiment was conducted, and the experiment as the bearingless motor with which both results were finally united was conducted.

The experiment of mock levitation which used the spring for the magnetic bearing and which actually applied the permanent magnet to the magnetic bearing were conducted, where, the conditions of having no rotation, flexibility is given only in the direction of Z-axis. In these experiments, it succeeded in levitation by 3mm to 3mm command. Next, the experiment of the mock magnetic levitation using the springs at the case of 1000 rpm was conducted. The mock magnetic levitation and rotation were performed by 3.05mm to 3mm command. From now on, the experiment which performed adjustment of the PID-gain and used the permanent magnet for the magnetic bearing will aim at levitating rotation.

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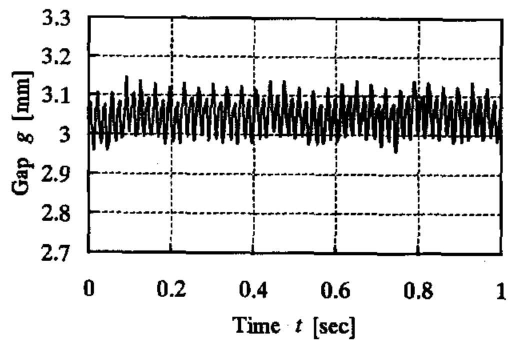

FIGURE 16: The experimental result of mock levitation on the disk-type motor at 1000 rpm.