Structures and Characteristics of Magnetic Bearing with Zero Power Controlled Electromagnetic Suspension

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***Abstract*— This paper proposes a new magnetic bearing in order to decrease rotor eccentricity and power consumption. The proposed bearing system consists of moving frames, suspensions, permanent magnets, electromagnets and Zero Power controller. The system enables to avoid rotor touchdowns. A clearance between a rotor and our proposed bearing may be increased compared to conventional electromagnetic bearings. The paper shows the experimental results to verify testing system.**

I. INTRODUCTION

There is Zero Power Control as a means to realize magnetic levitation by power saving. Zero Power Control enables to converge electromagnetic current to zero, using magnet units which consisted of permanent magnets and electromagnets, keeping a levitating object stable [1]. As application of this Zero Power Control, we aim at development of magnetic bearings with Zero Power Controlled electromagnetic suspension paying attention to the magnetic bearing which carries out non-contact support of a rotor. Power saving magnetic bearings can be constituted by applying Zero Power Control. Furthermore, since the gap between magnet units and a rotor can be set up greatly, the risk of touchdown can be reduced and improvement in reliability can be aimed at. However, if Zero Power Control is applied to magnetic bearings, a severe problem emerges. When a levitating rotor is subjected to external steady force, to keep equilibrium between external force and magnetic force, a position of levitating rotor may be changed. Therefore, when Zero Power Control is applied to the magnetic bearing, there is a problem that rotor eccentricity increases by external force. To overcome this difficulty, this paper proposes a new magnetic bearing structure with moving frames and suspensions. The structure enables to decrease a rotor eccentricity, and a risk of contacting touchdown bearings with fixed frames is reduced. The paper shows the experimental results to verify the system.

II. MAGNETIC BEARING WITH ZERO POWER CONTROLLED ELECTROMAGNETIC SUSPENSION

A. Structure of Magnetic Bearing

Fig. 1 shows the fundamental composition of magnetic bearings to propose. Magnet units are placed on opposite sides of moving frames, and a levitating rotor is placed between magnet units. Moving frames are supported by means of springs, and enable to displace according to the external force acting on the levitating rotor. Touchdown bearings are placed on fixed frames, and not interlocked with a motion of moving frames. The levitating rotor is biaxially controlled by placing magnetic support equipment in a vertical and horizontal direction of the levitating rotor.

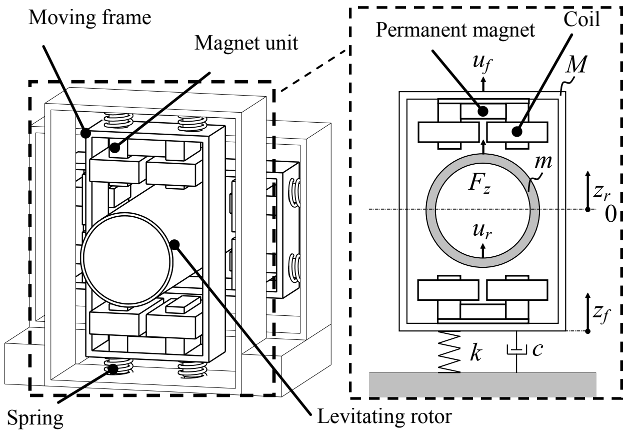

Fig. 1. Structure of Magnetic Bearing

B. Principle of fixed levitating position

As shown in Fig. 1, when the coupled model of magnetic levitation systems and spring systems is defined, motion equation for a levitating rotor and moving frames is given by equation (1) and (2).

$$m\left(\Delta\ddot{z}_r + \Delta\ddot{z}_f\right) = \frac{\partial F_z}{\partial z_r}\Delta z_r + \frac{\partial F_z}{\partial i_z}\Delta i_z + u_r \tag{1}$$

$$M\Delta\ddot{z}_f = -\frac{\partial F_z}{\partial z_r}\Delta z_r - \frac{\partial F_z}{\partial i_z}\Delta i_z - k\Delta z_f - c\Delta\dot{z}_f + u_f \tag{2}$$

where z_r is a gap between levitating rotor and magnetic units, z_f is the absolute position of moving frames, m is the mass of the levitating rotor, M is the mass of the moving frame, F_z is the total of the electromagnetic force received from the vertical or horizontal magnet units in a static state, i_z is exciting current, u_r is the external force acting on the levitating rotor, u_f is the external force acting on the moving frame, k is a spring constant, and c is a damping coefficient.

As $u_f = 0$, when the external force u_r acts on the levitating rotor, variation on the absolute position of the levitating rotor is represented by $\Delta z_r + \Delta z_f$. If Zero Power Control is applied, it is set to $i_z = 0$ in a static state. Therefore, when the time-derivative term is zero in equation (1), static displacement of the levitating rotor and the moving frame is given by equation (3).

$$\Delta z_r = -\frac{u_r}{\partial F_z/\partial z_r},\ \Delta z_f = \frac{u_r}{k} \tag{3}$$

Therefore, $\Delta z_r + \Delta z_f$ is given by equation (4).

$$\Delta z_r + \Delta z_f = -\frac{u_r}{\partial F_z/\partial z_r} + \frac{u_r}{k} \tag{4}$$

Therefore, if spring constant k equals to magnetic spring constant $|\partial F_z/\partial z_r|$, the absolute position of the levitating rotor is not be theoretically changed to static external force. There is previous work used this principle [2]. However, there is no example of application to a levitating rotor. By placing magnetic units in vertical or horizontal axis, High linearity area exists broadly. However, since it is not strict linearity, some variation arises (Fig. 2).

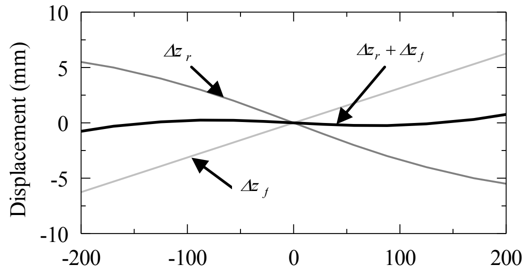

Fig. 2. Suspension property

C. Zero Power Controller

Fig. 3 shows the composition of Zero Power Controller. The control input u is calculated from the gain compensation loop which multiples gap and exciting current detected by displacement and current sensor, the change speed of the gap and external force acting on the levitating rotor by the gain F_d and the current integration loop which multiplies the integration value of exciting current by the gain K.

It is made to stabilize by designing each gain suitably. In addition, change speed and external force of the gap were presumed using the minimum dimension observer.

Voltage equation is given by equation (5). where e_z is exciting voltage, R is coil resistance, N is coil turns, ϕ_z is interlinkage magnetic flux, and L is inductance.

$$e_z = R\Delta i_z + N\frac{\partial \phi_z}{\partial z_r}\Delta \dot{z}_r + L\Delta \dot{i}_z \tag{5}$$

State equation is given by equation (6) derived from equation (1), (2), and (5).

$$\begin{cases} \dot{x} = Ax + bu + df \\ y = cx \end{cases} \tag{6}$$

where

$$x = \begin{pmatrix} \Delta z_r \\ \Delta z_f \\ \Delta \dot{z}_r \\ \Delta \dot{z}_f \\ \Delta i_z \end{pmatrix},\ A = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ a_{31} & a_{32} & 0 & a_{34} & a_{35} \\ a_{41} & a_{42} & 0 & a_{44} & a_{45} \\ 0 & 0 & a_{53} & 0 & a_{55} \end{pmatrix},\ b = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_{51} \end{pmatrix},$$

$$c = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix},\ d = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ d_{31} & d_{32} \\ 0 & d_{42} \\ 0 & 0 \end{pmatrix},\ f = \begin{pmatrix} u_r \\ u_f \end{pmatrix}$$

$$a_{31} = \left(\frac{1}{M} + \frac{1}{m}\right)\frac{\partial F_z}{\partial z_r},\ a_{32} = \frac{k}{M},\ a_{34} = \frac{c}{M},$$

$$a_{35} = \left(\frac{1}{M} + \frac{1}{m}\right)\frac{\partial F_z}{\partial i_z},\ a_{41} = -\frac{1}{M}\frac{\partial F_z}{\partial z_r},\ a_{42} = -\frac{k}{M},$$

$$a_{44} = -\frac{c}{M},\ a_{45} = -\frac{1}{M}\frac{\partial F_z}{\partial i_z},\ a_{53} = -\frac{N}{L}\frac{\partial \phi_z}{\partial z_r},$$

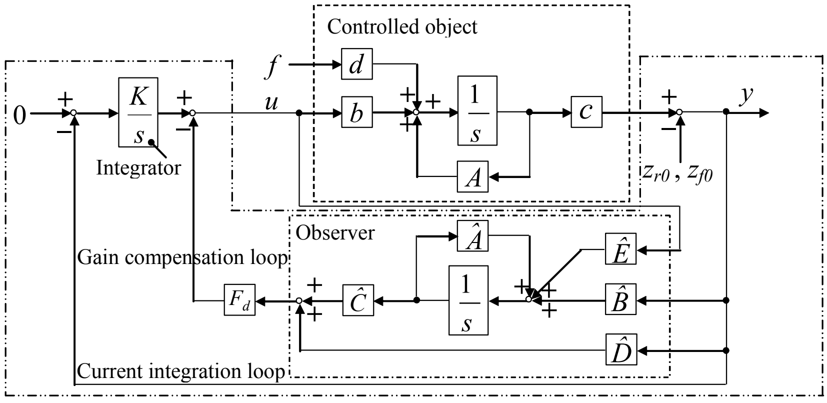

Fig. 3. Zero Power Controller

$$a_{55} = -\frac{R}{L},\ b_{51} = \frac{1}{L},\ d_{31} = \frac{1}{m},\ d_{32} = -\frac{1}{M},\ d_{42} = \frac{1}{M}$$

Moreover, u is a control input (exciting voltage e_z).

At this time, a control rule of Fig. 3 is given by equation (7).

$$u = -F_d \hat{x} - K\int y dt \tag{7}$$

where

$$F_d = \begin{pmatrix} F_1 & F_2 & F_3 & F_4 & F_5 & F_6 & F_7 \end{pmatrix},\ \hat{x} = \begin{pmatrix} \Delta z_r \\ \Delta z_f \\ \Delta \dot{z}_{rh} \\ \Delta \dot{z}_{fh} \\ \Delta i_z \\ u_{rh} \\ u_{fh} \end{pmatrix},$$

$$K = \begin{pmatrix} 0 & 0 & K_3 \end{pmatrix}$$

In addition, $\hat{x}$ is an output of the minimum dimension observer and is defined by equation (8).

$$\begin{cases} \dot{z}_{ob} = \hat{A} z_{ob} + \hat{B} y + \hat{E} u \\ \hat{x} = \hat{C} z_{ob} + \hat{D} y \end{cases} \tag{8}$$

where

$$z_{ob} = \begin{pmatrix} \Delta \dot{z}_{roh} \\ \Delta \dot{z}_{foh} \\ u_{roh} \\ u_{foh} \end{pmatrix},\ \hat{A} = \begin{pmatrix} -\alpha_1 & a_{34} & d_{31} & d_{32} \\ 0 & a_{44} - \alpha_2 & 0 & d_{42} \\ -\alpha_3 & 0 & 0 & 0 \\ 0 & -\alpha_4 & 0 & 0 \end{pmatrix},$$

$$\hat{B} = \begin{pmatrix} a_{31} - \alpha_1^2 + d_{31}\alpha_3 & a_{32} + a_{34}\alpha_2 + d_{32}\alpha_4 & a_{35} \\ a_{41} & a_{42} + (a_{44} - \alpha_2)\alpha_2 + d_{42}\alpha_4 & a_{45} \\ -\alpha_1\alpha_3 & 0 & 0 \\ 0 & -\alpha_2\alpha_4 & 0 \end{pmatrix},$$

$$\hat{C} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},\ \hat{D} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & 0 & 1 \\ \alpha_3 & 0 & 0 \\ 0 & \alpha_4 & 0 \end{pmatrix},\ \hat{E} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

α_1, α_2, α_3, α_4 are parameters which determine the poles of the observer. Laplace transform of equation (6), (7), and (8) is respectively carried out, and solved for state variables. As a result, it is given by equation (9).

$$X(s) = \left(sI - A + bF_d \hat{C}\left(sI - \hat{A}\right)^{-1} \hat{B}c + b\left(F_d \hat{D} + \frac{K}{s} \right)c \right)^{-1} \left(x_0 - bF_d \hat{C}(sI - A)^{-1} z_0 + dF(s)\right) \tag{9}$$

$\Phi(s)$ is defined by equation (10).

$$\Phi(s) \overset{def}{\equiv} \left(sI - A + bF_d \hat{C}\left(sI - \hat{A}\right)^{-1} \hat{B}c + b\left(F_d \hat{D} + \frac{K}{s} \right)c \right)^{-1} \tag{10}$$

$\Phi(s)$ is given by equation (11).

$$\Phi(s) = \frac{1}{\Gamma(s)\Gamma_{rob}(s)\Gamma_{fob}(s)} \begin{pmatrix} \phi_{11} & \phi_{12} & \phi_{13} & \phi_{14} & \phi_{15} \\ \phi_{21} & \phi_{22} & \phi_{23} & \phi_{24} & \phi_{25} \\ \phi_{31} & \phi_{32} & \phi_{33} & \phi_{34} & \phi_{35} \\ \phi_{41} & \phi_{42} & \phi_{43} & \phi_{44} & \phi_{45} \\ \phi_{51} & \phi_{52} & \phi_{53} & \phi_{54} & \phi_{55} \end{pmatrix} \tag{11}$$

The characteristic equation of proposed system is given by equation (12).

$$\Gamma(s)\Gamma_{rob}(s)\Gamma_{fob}(s) = 0 \tag{12}$$

where $\Gamma(s) = 0$ is a characteristic equation of a magnetic levitation control drive. $\Gamma_{rob}(s) = 0$ is a characteristic equation of the observer on the levitating rotor, and $\Gamma_{fob}(s) = 0$ is a characteristic equation of the observer on the moving frames. $\phi_{mn}(m,n = 1\sim5)$ is a polynomial of s. Stability of a system is aimed at by determining α_1, α_2, α_3, α_4, and feedback gains $F_1 \sim F_7$ that the characteristic root obtained from equation (11) is in left half area of s plane.

III. EXPERIMENT VERIFICATION

A appearance of verification magnetic bearing is shown in Fig . 4, and design specifications are given by Table 1. Non-contact support of the levitating rotor is carried out as a magnetic bearing by 2 axis control of vertical and horizontal sides, it is necessary to place the magnetic unit and moving frame of each axis so that it may operate independently. In that case, installation positions are shifted so that mutual operation may not interfere, and equipment is enlarged axially. Moreover, it is necessary to set up the control parameters independently since the operating point of the magnetic force which acts on the rotor differs. As a result, complication of control system design and decreased stability may be caused. Then, in 2 axis control, the vertical and horizontal frames are placed on the same plane as U-shaped frames. By this composition, the operating point of the magnetic force which acts on the rotor becomes the same, and it can make the same vertical and horizontal control drive designs.

The verification experiment of the rotational characteristic was conducted using the magnetic bearing of this composition. The action on the relative displacement of a rotor and a moving frame is shown in Fig. 5. The action on the moving frame is shown in Fig. 6. The action on the absolute position of the rotor is shown in Fig. 7. The response of exciting current is shown in Fig. 8. Although the relative position of a rotor and a moving frame, and the position of a moving frame are changed respectively, absolute position change of the rotor determined by the balance is a maximum of 0.4 (mm). Since the nominal gap of this equipment is set as 4 (mm), the rotor eccentricity rate showing the rate of the absolute position change to a nominal gap is set to 10 (%).

As a feature of an action, it turns out that absolute position change of a rotor is increasing in the 700 (rpm) neighborhood. This is a peak by the natural frequency of a magnetic levitation system. The natural frequency of a magnetic levitation system is determined by the response of control. If a control gain is set up highly, a response will go up and natural frequency will become high. This control drive designed so that natural frequency might be set to about 11 (Hz) in consideration of a response and stability. Therefore, it is the characteristic as a design mostly. Unlike the general magnetic bearing, this bearing has the double structure where a moving frame is arranged in a fixed frame. Although a rotor position change can be controlled, without increasing bearing stiffness theoretically, resonance of a moving frame exists according to double structure. The natural frequency of a moving frame is from 800 (rpm) to 900 (rpm), and if this is exceeded, exciting current increases to a maximum of 2 (A).

Characteristic of moving frames are shown in Fig .9. Spring has vibration free range and vibration isolation range. In the vibration free range, a rotor and a moving frame serve as a controlled object. However, since it is hard coming to move a moving frame in the vibration isolation range, it may be considered that a mass point is only a rotor. It is important for the characteristic to switch two control. The result of having switched control according to the characteristic of moving frames is shown in Fig. 10 and Fig. 11. This system balances rotor eccentricity rate and power consumption.

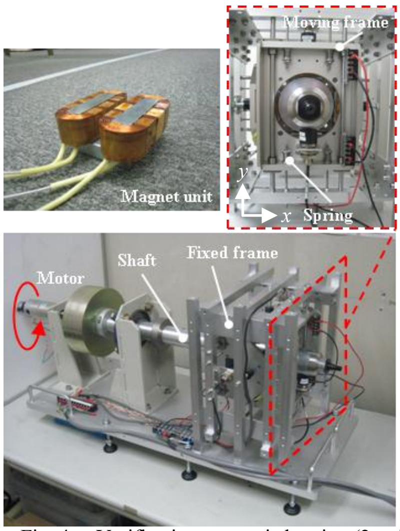

Fig. 4. Verification magnetic bearing (2-axis)

Table 1. Specification (2-axis)

Magnet unit	Outside dimensions	87 (mm)×87 (mm)×40 (mm)
	Magnet material	Nd-Fe-B
	Coil resistance	1.3 (Ω)
	Coil turns	250 (turn)
	Nominal gap	4 (mm)
Mechanical parts	Constant of spring	39.8 (N/mm)
	Levitation mass	5.8 (kg)

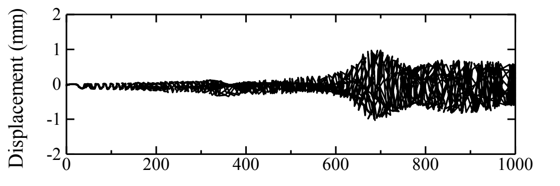

Fig. 5. Displacement between rotor and moving frame at *y* axis

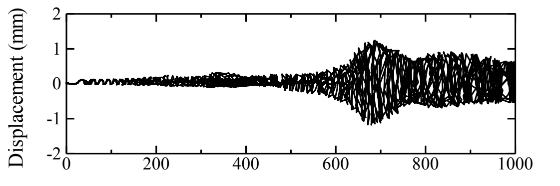

Fig. 6. Displacement of moving frame at *y* axis

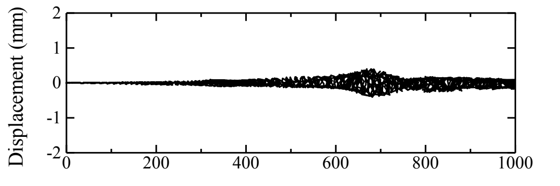

Fig. 7. Displacement of rotor at *y* axis

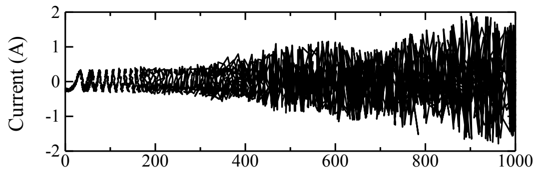

Fig. 8. Exciting current

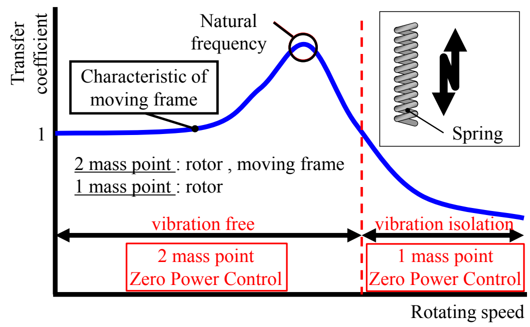

Fig. 9. Characteristic of moving frame

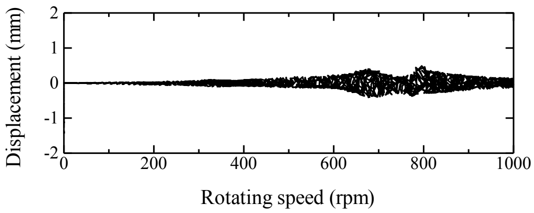

Fig. 10. Displacement of rotor with switching control

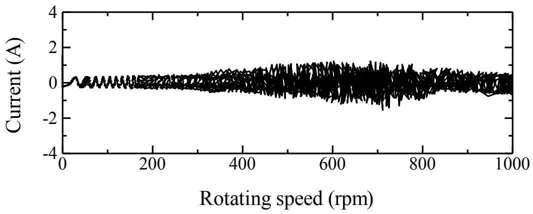

Fig. 11. Exciting current with switching control

IV. CONCLUSION

This paper proposes a new magnetic bearing in order to decrease rotor eccentricity and power consumption. Proposed bearing system consists of moving frames, suspensions, permanent magnets, electromagnets and Zero Power controller. The rate of the absolute position change to a nominal gap is set to 10 (%). The paper shows the experimental results to verify testing system.

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