# HYBRID HIGH $T_c$ SUPERCONDUCTING MAGNETIC BEARING (SMB) SYSTEM WITH NO BIAS CURRENTS

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## ABSTRACT

In this paper, a hybrid-type superconducting magnetic bearing (SMB) system with no-bias currents is discussed. The hybrid-type SMB system consists of passive-type SMB's, active-type magnetic bearings (AMB's), a rotor, and sensors. And the rotor position is controlled by a controller with no-bias currents. Because the controller doesn't need bias currents applied to the electromagnets, the energy losses are considered to be less than other magnetic bearing systems. The displacements of the rotor are suppressed by both the SMB's and the AMB's. The superconductors of the SMB's were field-cooled. Compliance for the bearings, displacements of the rotating rotor, and energy losses for the system were investigated. The results show that the hybrid-type SMB system with no-bias currents has good performances in these evaluations.


## INTRODUCTION

It is easy to obtain large levitation forces by using high $T_c$ (critical temperature) superconductors cooled in liquid nitrogen. Therefore, there have been many reports on application systems[(1)-(4)] based on the large pinning forces. Most of them are passive SMB's with superconductors and some permanent magnets for supporting the rotor. According to these papers, displacements of the rotor are as small as to be negligible. On the other hand, for the practical use of these applications, position change of the rotor due to magnetic flux creep or magnetic flux flow is unavoidable.

Our group has been studying the hybrid-type SMB system[(5)]. In this paper, conventional PID control was applied to the hybrid-type SMB system. Thus, the bias currents applied to the electromagnets were necessary to design the controller. In this paper, the SMB's in the system are considered to be dominant for suppressing the rotor displacements. Thus, a control method without bias currents is adopted to the system. Generally, it is difficult that controllers without bias currents for the linearization have so high gains. However, the controller without bias currents is applicable to our system

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because the SMB's are dominant in our system. In this paper, various kinds of dynamic evaluations concerning the system with no-bias currents were discussed.

## SYSTEM

The hybrid SMB system was built as shown in Fig.1. The hybrid SMB system consists of a pair of SMB's with superconductors and a pair of AMB's with electromagnets. The rotor measures 24mm in diameter and 158mm in length. It is composed of aluminum shaft with two sets of magnets for the SMB's and two sets of iron steels for the AMB's. The hybrid SMB system can operate as SMB system without control. The details about the SMB system have already been reported elsewhere[5]. In the hybrid SMB system, the SMB's are considered to be dominant for suppressing the rotor displacements, and the AMB's assist the SMB's to suppress the rotor displacements. Thus, control method with no bias currents is adopted to the hybrid SMB system. In the rotor control, currents don't excite both of the electromagnets facing each other simultaneously.

Here, we consider the control of the rotor, which is supported by the SMB's. Assuming the coordinate for the rotor as shown in Fig.2, the dynamic equations for the rotor are

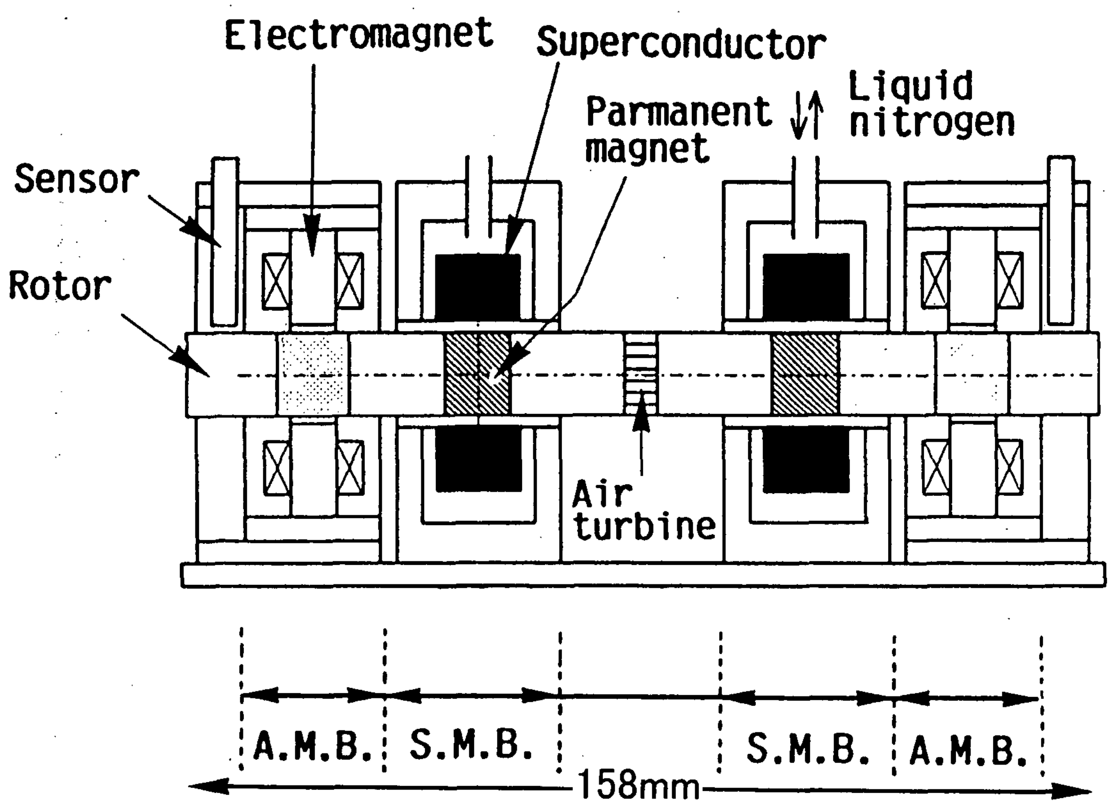


**Figure 1.** Schematic illustration of the hybrid SMB system. The system is composed of superconducting magnetic bearings (SMB's), active magnetic bearings (AMB's) and a rotor

$$m\ddot{x}_G + c\dot{x}_G + kx_G = f_{xL} + f_{xR} + f_{xd} \ , \tag{1}$$

$$J\ddot{\theta} + c_r\dot{\theta} + k_r\theta = -\ell_b f_{xL} + \ell_b f_{xR} + m_{\theta d} \ , \tag{2}$$

$$m\ddot{y}_G + c\dot{y}_G + ky_G = f_{yL} + f_{yR} + f_{yd} \ , \tag{3}$$

$$J\ddot{\phi} + c_r\dot{\phi} + k_r\phi = \ell_b f_{yL} - \ell_b f_{yR} + m_{\phi d} \ , \tag{4}$$

where $x_G$ and $y_G$ are displacements of the rotor, $f_{ij}$ $(i = x,y, \ \ j = L,R)$ are attractive forces for the rotor, $f_{id}$ $(i = x,y)$ are disturbances for the rotor, $\theta$ and $\phi$ are rotation angles for the rotor, $m_{ld}$ $(l = \theta,\phi)$ are moments for the rotor, $\ell_b$ is a distance between the electromagnet and the center of the rotor. And the rotor mass $m$, damping coefficient $c$, spring constant $k$, moment of inertia $J$, damping coefficient for rotation $c_r$, and spring constant for rotation $k_r$ are 0.37 kg, 46.1 N·s/m, $1.06\times10^5$ N/m, $7.91\times10^{-4}$ kg·m$^2$, $1.60\times10^{-2}$ N·m·s, and $7.81\times10^1$ N·m, respectively. The details of the modeling are reported in another report[6]. Then, the attractive forces $f_{ij}$ are written as

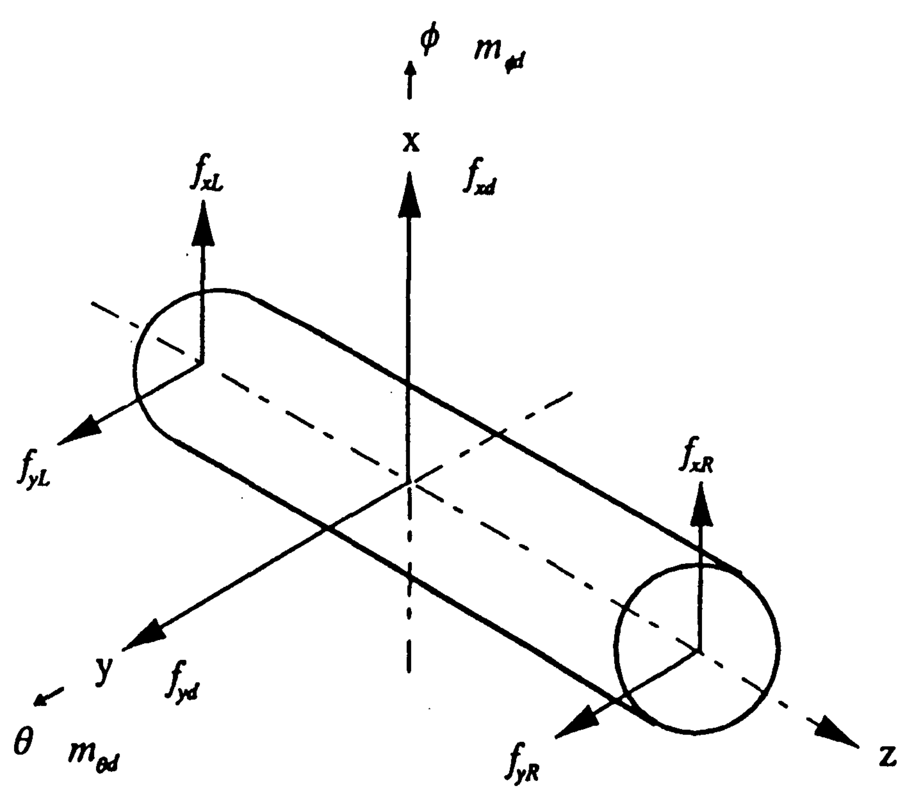


**Figure 2.** Coordinate for the rotor to design the controller.

$$f_{xL} = \frac{1}{2}K_f u_x - \frac{1}{2\ell_b}K_{fr}u_\theta \ , \tag{5}$$

$$f_{xR} = \frac{1}{2}K_f u_x + \frac{1}{2\ell_b}K_{fr}u_\theta \ , \tag{6}$$

$$f_{yL} = \frac{1}{2}K_f u_y + \frac{1}{2\ell_b}K_{fr}u_\phi \ , \tag{7}$$

$$f_{yR} = \frac{1}{2}K_f u_y - \frac{1}{2\ell_b}K_{fr}u_\phi \ , \tag{8}$$

where $u_i(i = x,y)$ and $u_l(l = \theta,\phi)$ are PID controller outputs, and $K_f$ and $K_{fr}$ are force gains. Only one of the facing electromagnets works for attracting the rotor according to the forces given by Eqs.(5)-(8). That is, both facing electromagnets don't work together. On the other hand, Consider that the displacement $x = w_x$ in the $x$ direction, the attraction forces applied to the rotor can be written as

$$f_{xj1} = k\left(\frac{i_{xj1}}{\ell_a - w_x}\right)^2, \quad (j = R,L) \tag{9}$$

$$f_{xj2} = k\left(\frac{i_{xj2}}{\ell_a + w_x}\right)^2, \quad (j = R,L) \tag{10}$$

where $f_{xj1}$ and $f_{xj2}$ indicate the attraction forces from the upper electromagnet and the attraction force from the lower electromagnet, respectively and $\ell_a$ is a rotor-electromagnet gap in the case that the rotor is in the center of the electromagnets. Because in the system applied currents to the electromagnets are given by

$$i_{ijn} = -k_a V_{ijn}, \ (n = 1,2) \tag{11}$$

where $k_a$ is an amplifier gain, the current $i_{ijn}$ is positive in the case $V_{ijn} < 0$ and let the currents $i_{ijn}$ be zero in the case $V_{ijn} > 0$. From Eqs.(9)-(11), applied voltages become

$$V_{ij1} = -\frac{1}{k_a}\sqrt{\frac{f_{ij1}}{k}}\left(\ell_a - w_i\right), \tag{12}$$

$$V_{ij2} = -\frac{1}{k_a}\sqrt{\frac{|f_{ij2}|}{k}}\left(\ell_a + w_i\right). \tag{13}$$

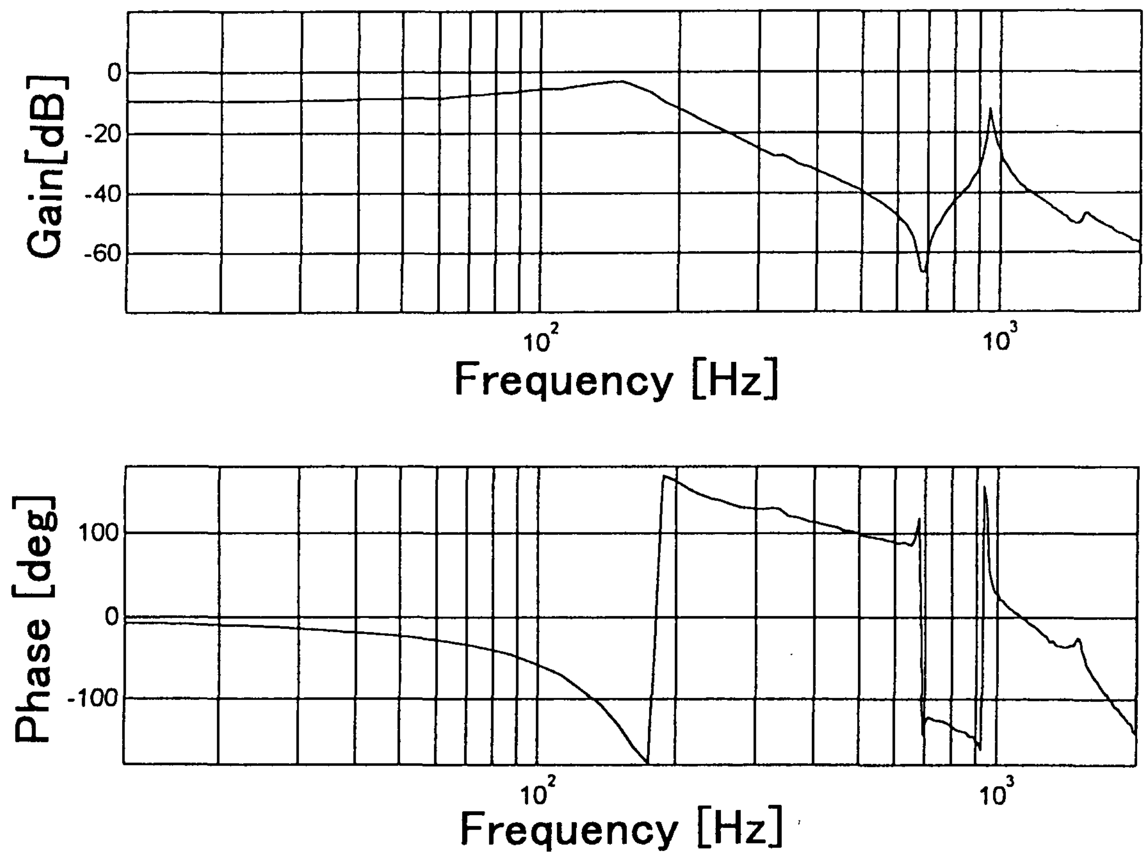


**Figure 3.** Closed loop characteristics of the cylindrical motion in the vertical direction for the hybrid-type SMB system.

Finally, Eqs.(12) and (13) can be written as

$$V_{ij} = sign(f_{ij})\frac{1}{k_a\sqrt{k}}\sqrt{|f_{ij}|}\left\{\ell_a - sign(f_{ij})w_i\right\}, \tag{14}$$

where

$$sign(f_{ij}) = \begin{cases} 1\,, & f_{ij} > 0 \\ 0\,, & f_{ij} = 0 \\ -1, & f_{ij} < 0 \end{cases} \tag{15}$$

and the force in the $x$ direction is considered to be positive in Eq.(14).

In the hybrid SMB system, the rotor mass is supported by both the SMB's and the AMB's with the control above mentioned. The controller gains were tuned by using the stability analysis for open loop system. The closed loop characteristics of the cylindrical motion for the hybrid SMB system are shown in Fig.3. The gains are almost constant in the

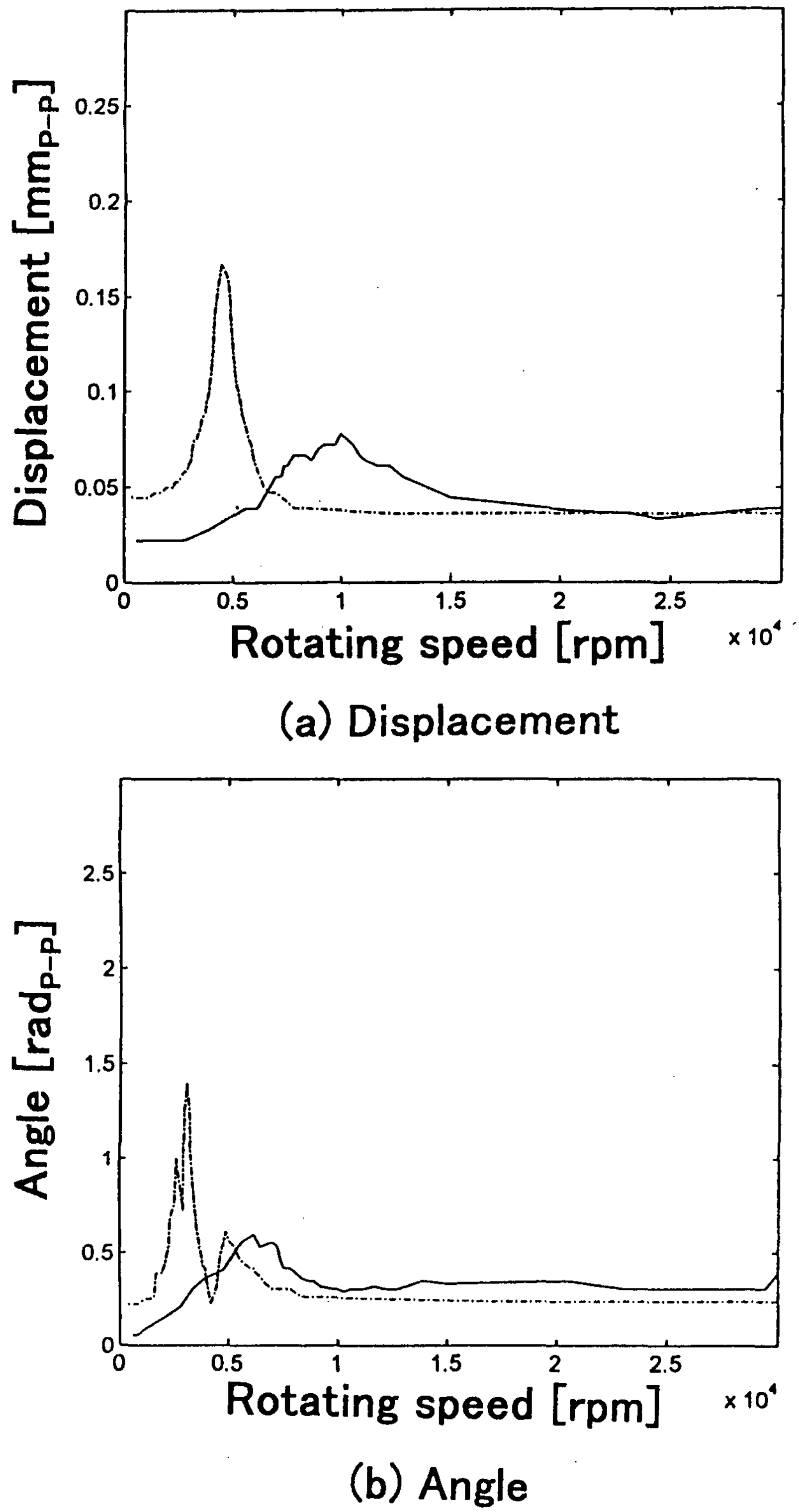


**Figure 4.** (a) The displacement and (b) the rotation angle in the vertical direction for the hybrid SMB (solid line) and the SMB without control (dotted line).

frequency range less than 70Hz.

## DYNAMIC CHARACTERISTICS

Displacements of the rotating rotor in the speed range less than 30,000rpm were evaluated. Fig.4 shows (a) the cylindrical motion and (b) the conical motion in the vertical direction. From Fig.4, it is found that the displacements for the SMB system in the speed range more than 15,000 rpm are less than 50$\mu$m, and the rotation angles in the speed range more than 10,000rpm are less than 0.4rad. This is because the center of gravity of the rotor is off-centered. The displacements and the rotation angles for the SMB system without control near the resonance rotating speeds are relatively large. On the other hand, the

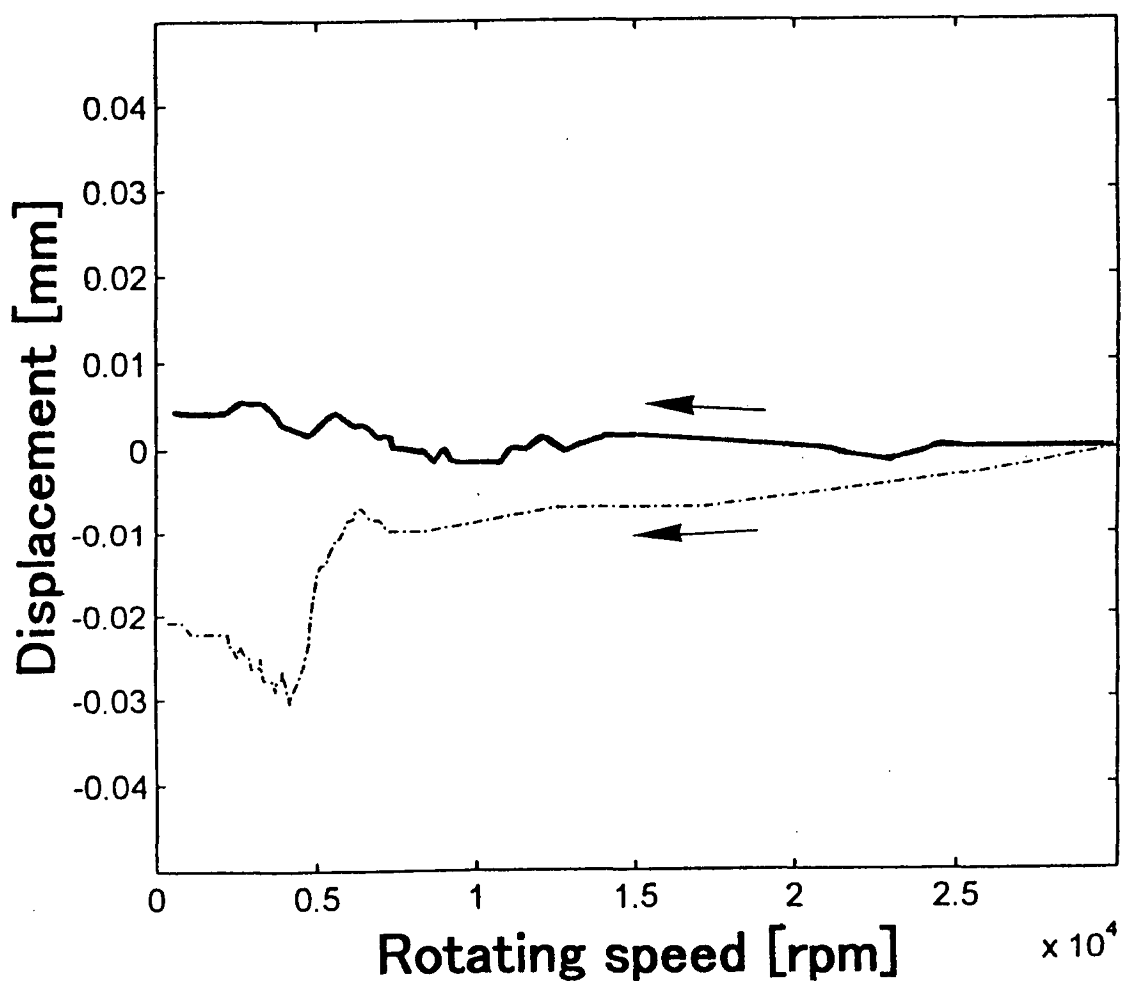


**Figure 5.** Relationship between the displacement and the rotating speed for the hybrid SMB system (solid line) and the SMB system without control (dotted line).

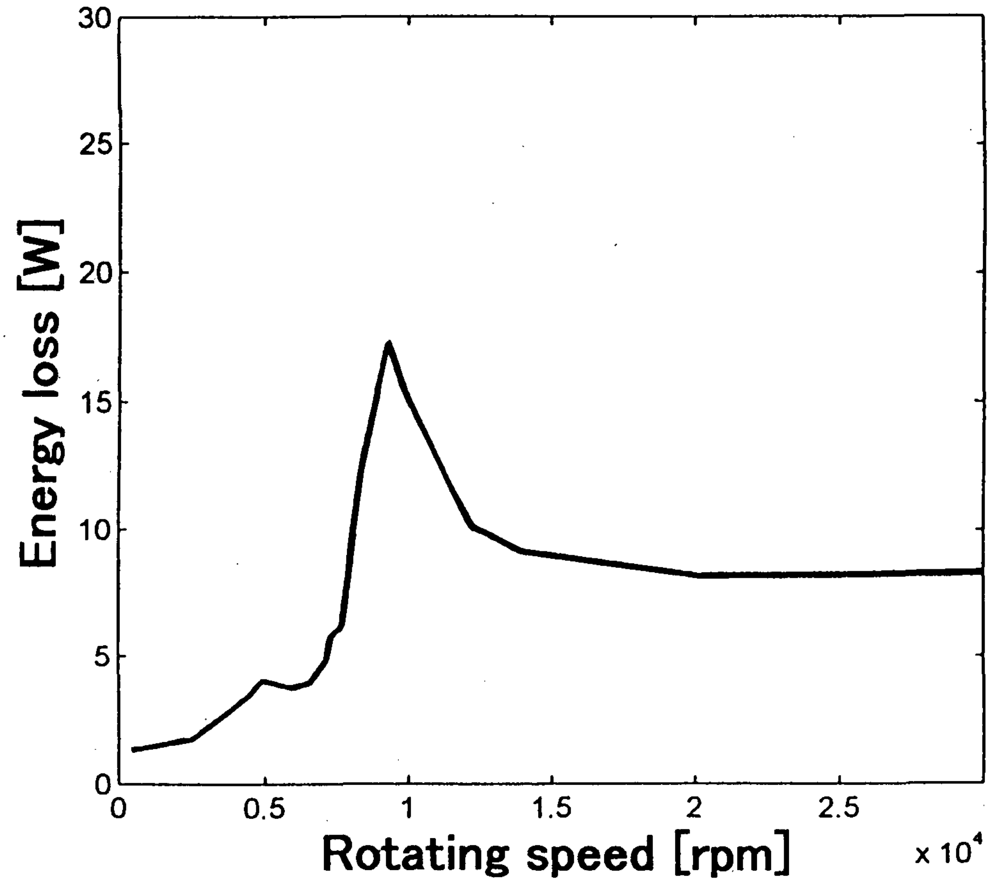


**Figure 6.** Relationship between the energy loss and the rotating speed of the rotor for the hybrid SMB system.

displacements and rotation angles for the hybrid SMB system are smaller than those for the SMB system without control in the speed range less than 15,000 rpm, and the displacements and the angles for the hybrid SMB system are almost the same as those for the SMB system without control in the speed range more than 15,000rpm. This shows that the controller of the hybrid SMB system is effective for the vibrations in the resonance speed range less than 15,000rpm and that the controller is not effective in the speed range more than 15,000rpm. These characteristics are desirable for the hybrid SMB system.

For the purpose of investigating the efficiency of the hybrid SMB system, experiments for pinning effect in the superconductors were performed. After the rotor spun up to a speed of 30,000rpm using PID control, the displacement changes for the hybrid SMB system and the SMB system without control were investigated. The experimental results for the spin down tests are shown in Fig.5. The displacements for the SMB system without control become large with decreasing rotating speed. This is due to the magnetic flux creep and the magnetic flux flow. On the other hand, the displacements for the hybrid SMB system are almost constant at zero except for the resonance speed. This shows that the control is effective for the system with respect to the pinning effect.

Energy loss for the hybrid SMB system was evaluated. The total energy loss for the hybrid SMB system was calculated using the applied voltage to the electromagnets of the hybrid SMB system. Just electrical energy loss is treated in the energy loss here, though there is another energy loss related to liquid nitrogen consumption. Because a proper thermal insulation in the space could prevent the liquid nitrogen consumption. Fig.6 shows the relationship between the energy loss and the rotating speed of the rotor. The energy loss in the speed range around 10,000rpm is larger than that in the other speed ranges, and the energy loss in the speed range more than 15,000rpm is almost constant. This is because the controller works to suppress the displacements just near the resonance speed.

## SUMMARY

Dynamic characteristics for the hybrid-type SMB system composed of SMB's, AMB's, and a rotor are studied. A controller with no-bias currents is designed for suppressing the rotor displacements. The results show that the displacements of the rotating rotor for the cylindrical motion and the conical motion are suppressed well near the resonance speed ranges. In the spin down tests, the displacement change due to the magnetic flux creep and the magnetic flux flow for the hybrid-type SMB system is better than the system without control. This shows that the control adopted here for the hybrid-type SMB system is effective. From the evaluation of the energy losses for the system, it is found that the control of the system is useful in the speed range more than 15,000rpm.

From the results shown here, it is found that there are some possible applications of the hybrid SMB system to liquid nitrogen/helium pumps, fly wheels/bearings used in the space, etc.

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