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A Hybrid-type Superconducting Magnetic Bearing (SMB) System with the Rotor Supported by SMBs

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Abstract: *A hybrid-type SMB system consisting of SMBs, active magnetic bearings (AMBs) has been developed for the purpose of studying the practical use of superconducting magnetic bearings (SMBs). The hybrid-type SMB system does not need bias currents applied to the electromagnets for supporting the rotor. The displacements of the rotor position are suppressed by both the SMBs and the AMBs. Dynamics in the hybrid-type SMB system, the system with only SMBs working, and the system with only AMBs working are investigated. The results show that the hybrid-type SMB system has a good performance in them.*

1 Introduction

Applying high T_c (critical temperature) superconductors to industrial fields is very promising. Superconductors prepared by Quench-Melt-Growth (QMG) process, and other new methods show good properties such as strong pinning force useful for industrial applications [1]-[4]. Moreover, it is easy to obtain large levitation forces by using high T_c superconductors cooled in cheap liquid nitrogen. Stable levitation systems with neither contacts nor additional control mechanisms can be realized using high T_c superconductors.
Among many applications of high T_c superconductors to industrial fields, efforts have been put into the development of SMB systems [5]-[7] and fly wheel systems [8,9] based on the large pinning force. Most of them are passive-type SMB systems with some permanent magnets and superconductors for supporting the rotor. According to these papers, displacements of the rotor are as small as to be negligible. On the other hand, for practical use of SMB systems and flywheel systems, resultant position change of the rotor due to magnetic flux creep or magnetic flux flow is unavoidable [1]-[4]. When large disturbance forces are applied to the rotor, the rotor position changes to another stable position because of magnetic flux creep or magnetic flux flow. This is inevitable as long as passive-type SMB systems are used.
In order to overcome the week point in passive-type SMB systems, our group has developed a hybrid-type SMB system.

2 System

2.1 Structure

The hybrid-type SMB system was built as shown in Fig. 1. The hybrid-type SMB system consists of a pair of SMBs with superconductors and a pair of AMBs with electromagnets. Thus, the system can operate as a system with only SMBs working or as a system with only AMBs working. The rotor, 24 mm in diameter and 158 mm in length, is composed of an aluminum shaft, two sets of four ring magnets for the SMBs, and two sets of magnetic steels for the AMBs. The sets of magnets have a pole order of NS-SN-NS-SN with an axial magnetization of $B_r \fallingdotseq$ 1.0 T. Each ring magnet is OD24×ID8×4.3 mm in size. The housings of the SMBs are composed of cylindrical superconductors (OD45×ID25.6×16mm, $J_c \fallingdotseq 10^8$ A/m^2 at 1.0T), which are shaped like a doughnut. The housings of the AMBs are composed of eight pieces of electromagnets with solenoids of 300 Turn (0.3mm ϕ). Four eddy current sensors are installed in the system to measure the displacements of the rotor.

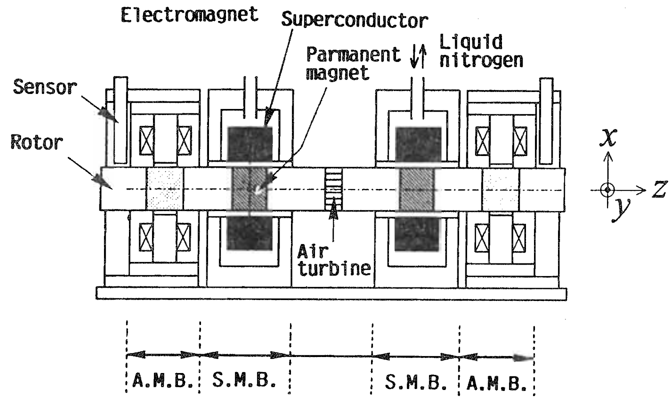

Fig.1. Schematic illustration of (a) the hybrid-type SMB system, (b) the section of the AMB, and (c) the section of the SMB.

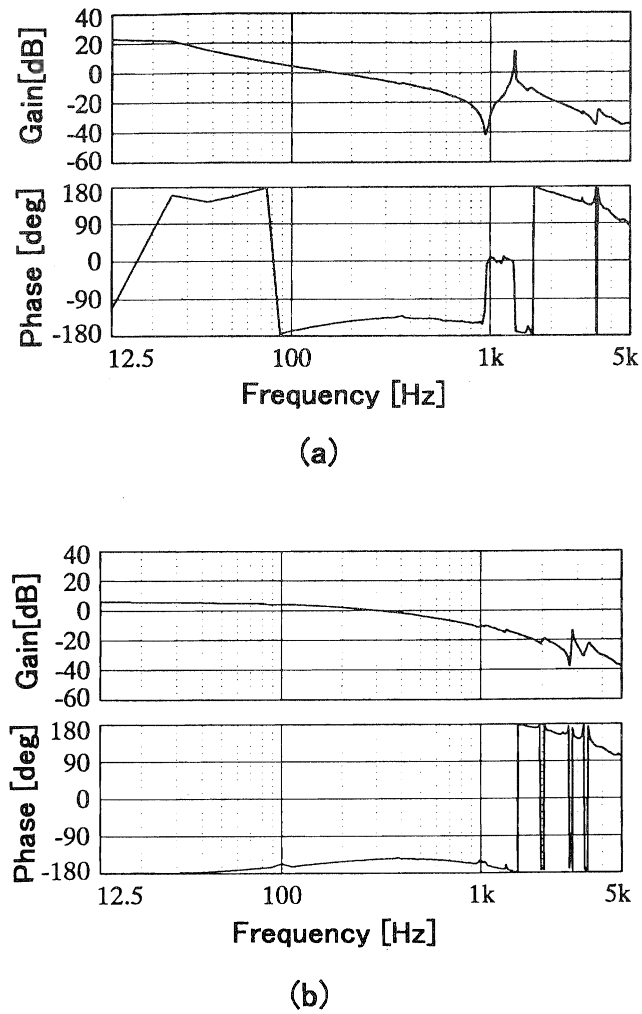

Fig.2. Open loop characteristics of (a) the translatory motion and (b) the conical motion of the hybrid-type SMB system in the vertical direction.

The superconductors of the hybrid-type SMB system are cooled, in the state that the rotor is levitated in the center of the bearings by the AMBs. In other words, the superconductors of the system are field-cooled. After that, the rotor is changed to a desired position as the bias currents applied to the electromagnets become zero. Thus, the rotor is supported by the SMBs during the experiments. During the experiments, liquid nitrogen in the tank is circulated to reduce the pressure of the nitrogen tank.

The hybrid-type SMB system can also work as a system with only SMBs working or as a system with only AMBs working. In the experiments, we used both of the system with only SMBs working and the system with only AMBs working to compare the hybrid-type SMB system with these systems. In the case of the hybrid-type SMB system, it does not need bias currents to support the rotor. In the case of the system with only AMBs working, the system needs bias current to support the rotor, that is different from the hybrid-type SMB system. Thus, the stiffness of the system with only AMBs working is different from the AMB stiffness of the hybrid-type SMB system.

2.2 Open loop characteristics

We applied the stability analysis to the open loop of the hybrid-type SMB system. Fig. 2 shows the open loop characteristics of the hybrid-type SMB system. Figs. 2 (a) and (b) represent the open loop characteristics of translatory motion and that of conical motion in the vertical direction, respectively. The gain peak at frequency of 1300 Hz represents the first bending mode of the rotor. The gain margin and the phase margin are 11.8 dB and 30.4 degree, respectively. Gain margins and phase margines in other motions are almost the same values. The frequencies showing the gain margins of the system are more than 1kH. The frequencies showing the phase margins are in the range from 100 to 330 Hz. These results show that it is found that the stability analysis in open loop system is available for the hybrid-type SMB system.

3 Impulse response

3.1 Experimental results

Impulse responses of the hybrid-type SMB system, the system with only SMBs working, and the system with only

AMBs working were investigated. The impulse forces were applied to the stationary rotor in the radial direction. The displacements of the rotor detected by the eddy current sensors were measured by using a FFT analyzer.

Figs. 3, 4, and 5 show the impulse responses (solid lines) of the system with only SMBs working, the system with only AMBs working, and the hybrid-type SMB system, respectively. In each figure, Figs. (a) and (b) correspond to a free vibration curve of translatory motion and that of conical motion, respectively. The first displacement of the response is controlled to be within the range from 80 to 100 μm in the translatory motion, and within the range from 4×10^{-4} to 5×10^{-4} rad in the conical motion.

Damped free vibration curves (solid line) are observed as shown in Figs. 3. The amplitudes of the curves seem to decrease exponentially. After the damped vibrations, the amplitudes return to zero. This shows that the rotor is self-centered in the translatory motion and in the conical motion. The settling times for Figs. 3 (a) and (b) are less than 100 ms and 400ms, respectively. The settling time for vibration in Fig. 3 (b) is about 3 times longer than that in Fig. 3 (a). This is because the SMBs are located near the center of the rotor. The impulse response for the system with only AMBs working has large damping as shown in Fig. 4. The settling times for Figs. 4 (a) and (b) are less than 50 ms and 60 ms, respectively. These are almost the same values. Also, both of the settling times in the translatory motion and the conical motion for the hybrid-type SMB system are less than 20 ms as shown in Fig.5. We can not compare the three systems, because the locations of the SMBs and the AMBs are different from each other, and because the stiffness of the system with only AMBs working is different from the AMB stiffness of the hybrid-type SMB system, as mentioned previously. After all, it is found that the results for the hybrid-type SMB system are better than the other systems in the view point of settling time.

3.2 Modeling

Because the displacements of the rotor are small, the rotor position change to another stable position is negligible.

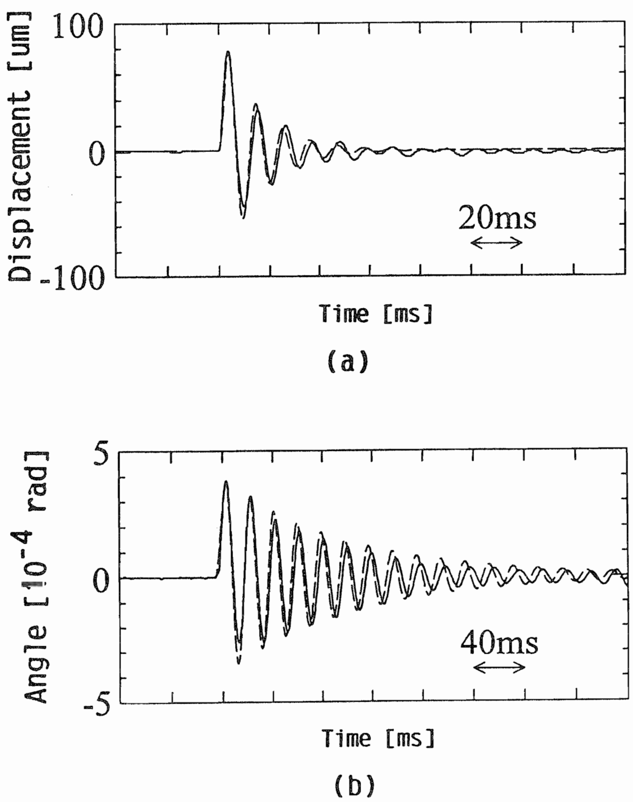

Fig.3 Impulse responses of the system with only SMBs working, in the vertical direction. The solid lines show experimental results and the dotted lines simulation ones.

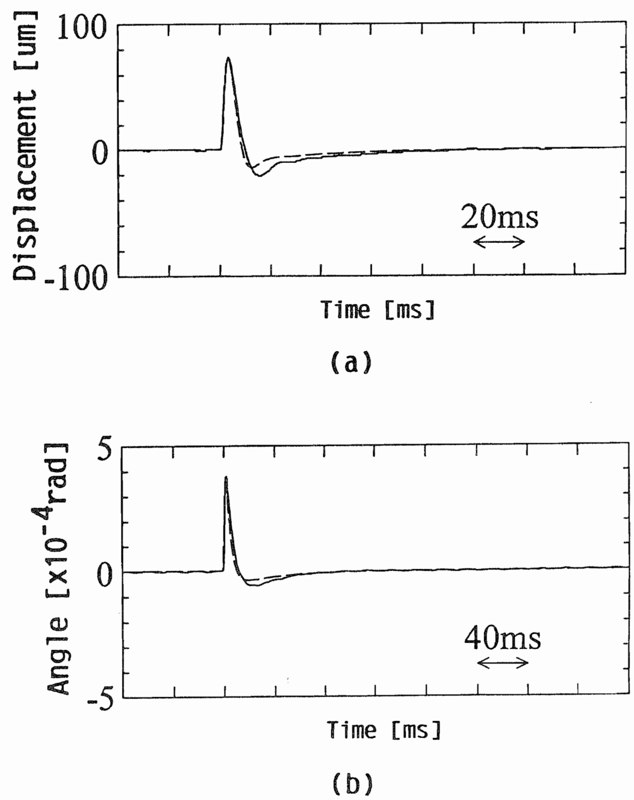

Fig.4 Impulse responses of the system with only AMBs working, in the vertical direction. The solid lines show experimental results and the dotted lines simulation ones.

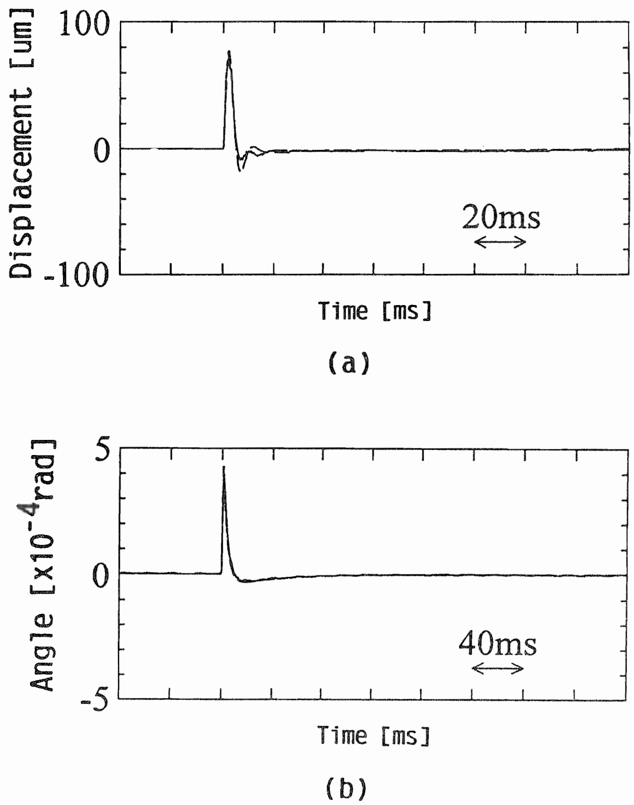

Fig.5 Impulse responses of the system with only AMBs working, in the vertical direction. The solid lines show experimental results and the dotted lines simulation ones.

Thus, dynamic model of the system with only SMBs working in the translatory motion is presented by

$$m\ddot{x} + c_s\dot{x} + k_s x = F_d , \qquad (1)$$

where m : rotor mass, c_s : damping coefficient, k_s: spring constant, F_d: disturbance force, and x : displacement of the rotor. The parameters c_s and k_s representing the dynamic models of the system with only SMBs working can be obtained experimentally. On the other hand, dynamic model of the system with only AMBs working in the translatory motion is presented by

$$m\ddot{x} + c_a x + k_a x + K_{Ix}\int xdt = F_d , \qquad (2)$$

where c_a : damping coefficient, k_a: spring constant, K_{Ix}: constant coefficient for integral. The parameters in Eq. (2) are obtained experimentally and theoretically. Thus, the dynamic model of the hybrid-type SMB system in the translator motion can be written by

$$m\ddot{x} + cx + kx + K_{Ix}\int xdt = F_d , \qquad (3)$$

where $c = c_s + c_a$ and $k = k_s + k_a$. Eq. (3) is transformed into

$$\ddot{x} + 2\gamma\omega_n\dot{x} + \omega_n^{\ 2} x + \frac{K_{Ix}}{m}\int xdt = \frac{F_d}{m} , \qquad (4)$$

where $\gamma = c/2\sqrt{mk}$, $\omega_n = \sqrt{k/m}$, and $\omega_d = \omega_n\sqrt{1-\gamma^2}$. Dynamic model of the hybrid-type SMB system in the conical motion can be obtained in the same way.

3.3 Simulations

Parameters representing the dynamic models of the system with only SMBs working, the system with only AMBs working, and the hybrid-type SMB system can be obtained theoretically and experimentally.

Simulation of the impulse responses were carried out using the parameters. The impulse forces were tuned to fix the displacements of the experimental results. Because the impulse forces used in the experiments were not ideal ones. The simulation results are shown in Figs. 3 – 5 as dotted lines. It is found that the simulation responses resemble the experimental responses. This shows that the dynamic parameters are appropriate and that it is possible that the hybrid-type SMB system is modeled using dynamic parameters of spring constant and damping coefficient.

4 Displacements of the rotating rotor

Displacements of the rotating rotor in the speed range less than 30,000 rpm were evaluated. The displacements in the x direction were measured by using the upper sensor on the left. Therefore, the displacements caused by the translatory motion and the conical motion are included in the experimental results. Because the rotor used here is symmetrical in the center of the rotor. In the experiments, displacements for the hybrid-type SMB system, the system with only SMBs working, and the system with only AMBs working were investigated.

Figure 6 shows the relationship between the displacements and the rotating speeds of the rotor for the hybrid-type SMB system, the system with only SMBs working, and the system with only AMBs working, which correspond to the three types of lines as shown in Fig. 6. The displacements of the system with only SMBs working in the speed range more than 10,000 rpm are less than 100 μm, which are contributed to that the center of gravity of the rotor is off-centered. Therefore, the system with only SMBs working is satisfactory in this range. On the other hand, the displacements of the system are relatively large in the speed range less than 8,000 rpm. There are two

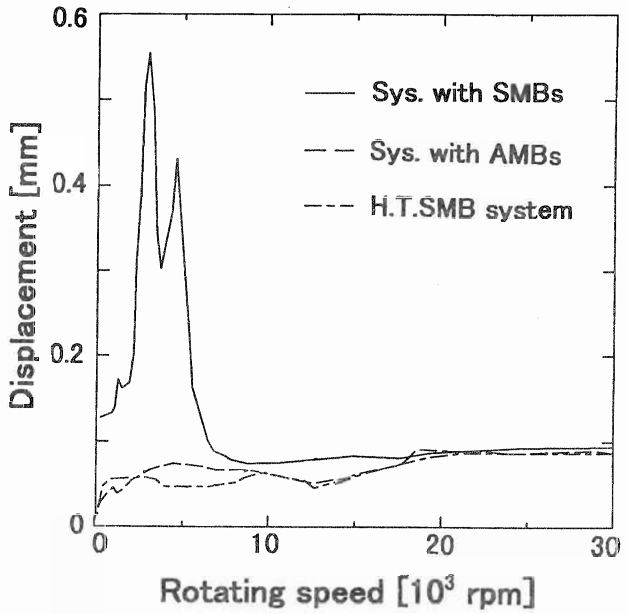

Fig. 6 Relationship between the displacements and the rotating speeds of the rotors for the hybrid-type SMB system, the system with only SMBs working, and the system with only AMBs working.

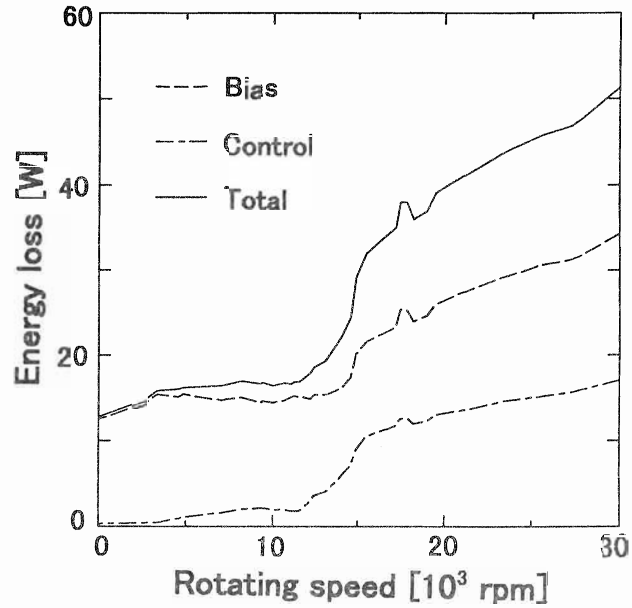

Fig.7 Relationship between the energy loss and the rotating speed of the rotor for the system with only AMBs working.

displacement peaks at ~3,000 and ~5,000 rpm, which correspond to conical motion and translatory motion, respectively. The displacements of the hybrid-type SMB system are suppressed more than those of the system with only SMBs working in the speed range less than 8,000 rpm. This is because the system works with both SMBs and AMBs. The displacements of the system with only AMBs working are almost equal to those of the hybrid-type SMB system. However, in this case, we can not compare the hybrid-type SMB system with the system with only AMBs working. Because the stiffness of the system with only AMBs working is larger than the AMB stiffness of the hybrid-type SMB system, as previously mentioned. Anyway, the hybrid-type SMB system is available for suppressing the rotating rotor displacements.

5 Energy loss

Energy loss of the systems was evaluated in order to study the energy saving of the hybrid-type SMB system. The total energy lost by the hybrid-type SMB system was calculated using the applied voltage to the amplifiers. Here, the energy loss on the left AMBs is considered to be equal to those on the right AMBs.

Figure 7 shows the relationship between the energy loss and the rotating speed of the rotor for the system with only AMBs working. The total energy loss is the sum of the loss used for the bias currents/voltages always applied to the electromagnets and the loss used for the control currents/voltages applied to them. Therefore, the loss for the control in the lower speed range less than 10,000 rpm is almost zero and the loss for the bias in the same speed range is almost constant. On the other hand, the losses for the bias and the control increase monotonously in the speed range more than 10,000 rpm. This is because the differentiation of the PID controller is dominant with the increasing frequency.

The relationship between the energy loss and the rotating speed of the rotor for the hybrid-type SMB system is shown in Fig. 8. As shown in Fig. 8, the loss for the control in the lower speed range less than 10,000 rpm is almost zero and the loss for the bias in the same speed range is almost constant. In the speed range more than 10,000 rpm, the losses for the bias and the control increase monotonously. These characteristics resemble those shown in Fig. 7. However, in the whole speed range less than 30,000 rpm, the loss for the bias in Fig. 8 is smaller than that in Fig. 7. The resulting total energy loss for the hybrid-type SMB system in Fig. 8 is also smaller than that in Fig. 7. This is because the hybrid-type SMB system does not need the bias current to support the rotor since the SMBs in the system support the rotor.

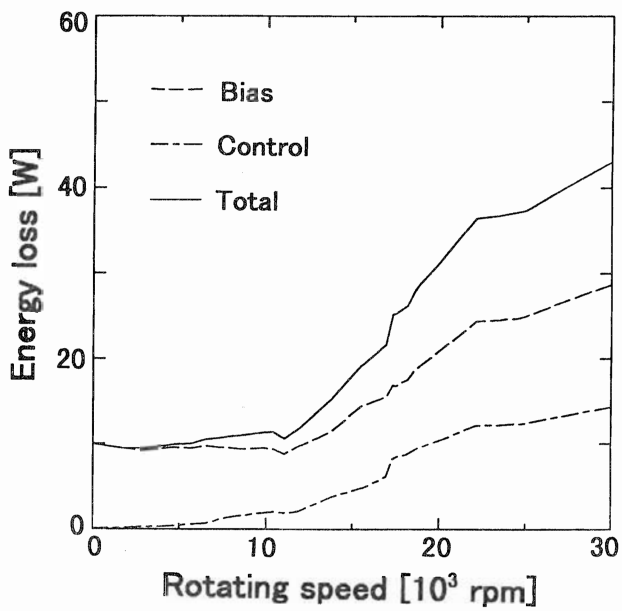

Fig.8 Relationship between the energy loss and the rotating speed for the hybrid-type SMB system.

6 Summary

A hybrid-type superconducting magnetic bearing system has been developed. The bearing system consists of SMBs, AMBs, and a rotor with two sets of ring magnets and two sets of magnetic steels. The bearing system can work as the system with only SMBs working or as the system with only AMBs working. The rotor mass is supported by the SMBs and the displacements are suppressed by both the SMBs and the AMBs. It is possible that the hybrid-type SMB system is modeled using dynamic parameters of spring constant, and damping coefficient. The simulation results and the experimental results show that it is found that the modeling is appropriate. The displacements of the hybrid-type SMB system are suppressed more than those of the system with only SMBs working in the speed range less than 8,000 rpm. In the whole speed range less than 30,000 rpm, the loss of the hybrid-type SMB system is smaller than that of the system with only AMBs working. The hybrid-type SMB system is considered to be effective as a new type bearing system.

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