Static and Dynamic Characteristics of Superconducting Magnetic Bearings Using MPMG Y-Ba-Cu-O*

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Measurements of the static forces were performed for various types of superconducting magnetic bearings at liquid nitrogen temperature. It was found that the stiffness of the superconducting bearing was rather small; however, both the electromagnetic forces and the stiffness could be increased by using a combination of a thrust and radial bearing. It was also found that the stiffness could be increased by using the attractive force due to flux pinning. Based on these measurements, a practical superconducting magnetic bearing was designed and constructed, where a 2.4 kg rotor could rotate at 33 000 rpm.

Key Words: Superconducting Bearing, Y-Ba-Cu-O, Static Force, Dynamic Characteristics, Stiffness, Whirling

1. Introduction

The discovery of oxide superconductors, which superconduct above the boiling point of liquid nitrogen, has opened up a number of novel applications of superconductors. One such application is the magnetic bearing, where the repulsive force of a superconductor is used to support rotating shafts, and thus a frictionless bearing can be constructed without any complex control. However, as long as we use the Meissner effect or the perfect diamagnetism, the upper limit of the magnetic field is too small to be used for any practical applications.

Recently, it has been shown that a large repulsive or attractive force can be obtained by the electromagnetic interaction of the superconductors, when they exhibit flux pinning⁽¹⁾. Large pinning forces have been

achieved in the Y-Ba-Cu-O superconductors prepared by the melt-powder-melt-growth (MPMG) process, where fine Y_2BaCuO_5 particles are dispersed in the $\text{YBa}_2\text{Cu}_3\text{O}_7$ matrix, and are considered to act as pinning centers⁽²⁾. Since the development of such bulk superconductors with large electromagnetic forces, many studies have been conducted to construct practical magnetic bearings⁽³⁾⁻⁽⁵⁾.

There are many reports on the force measurements of disk Y-Ba-Cu-O superconductors, mainly under static conditions. Although these studies have dealt with the hysteretic behavior of the force against the distance, its mechanism has not been clarified.

Using the data of static measurements, several prototype superconducting bearings have been constructed. Moon and Chang⁽⁶⁾ have succeeded in rotating a 0.5 kg rotor at 20 000 rpm. Yotsuya et al.⁽⁷⁾ and Yokoyama et al.⁽⁸⁾ have also rotated a 1 kg shaft at 5 000 rpm and a 1.1 kg shaft at 4 500 rpm, respectively. These bearings utilize disk superconductors. The authors have also succeeded in rotating a 2.4 kg shaft at over 30 000 rpm, where ring superconductors are used as stators. This ring type of superconducting stator seems to be more suitable for practical applications.

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In this paper, we first report the results of static force measurements of the superconducting bearing with ring Y-Ba-Cu-O stators. Second, we analyze the data based on superconducting properties of pinned type II superconductors. Finally, we report the dynamic characteristics of the superconducting bearing.

2. Experimental

2.1 Sample preparation

Figure 1 shows a schematic view of the superconducting bearing. The stator was made of a Y-Ba-Cu-O superconductor fabricated by the MPMG process, of which details have been reported elsewhere⁽²⁾. The sample has a J_c value of 30 000 A/cm² at 77 K and 1 T when the field is applied parallel to the c axis. Because of a large anisotropy, the J_c value drops to 10 000 A/cm² when the field is applied perpendicular to the c axis. It is also important to note that J_c values are dependent on the oxygen content of the sample, and it is difficult to fully oxygenate a large sample, which inevitably lowers the overall J_c and thus the levitation force.

The ring with dimensions of $\phi 65 \times \phi 40 \times t 20$ was cut from a large MPMG-processed Y-Ba-Cu-O superconductor. This ring superconductor was glued to a container, which could be thermally insulated. Liquid nitrogen can flow within this container and cool the superconductor. There is a gap between the superconductor and the inner wall of the container, so that the superconductor can be cooled effectively. Typical dimensions of the parts used for the bearing are tabulated in Table 1. The properties of Fe-Nd-B magnets used in this study are: $Br=11.2$ kG; $bH_c=10.5$ kOe; and $BH_{\max}=30$ MGOe.

2.2 Static measurements

Figures 2 and 3 show schematic drawings of the apparatuses used to measure static properties of a thrust bearing and a radial bearing, respectively. In the case of thrust bearing properties, the gap between the bearing and a magnet is controlled by using the adjusting nuts, and the force is detected using a load cell. For a radial direction, the gap is controlled by a micrometer.

Table 1 Dimensions of Superconducting Magnetic Bearing

Superconductor	$\phi 65 \times \phi 40 \times t 20$
Thrust magnet	$\phi 65 \times \phi 40 \times t 8$
Radial magnet	$\phi 36 \times \phi 25 \times t 20$
Inner dia. of Shield plate	$\phi 38$
Thickness of Shield plate	0.6 mm

Static measurements for the apparatus shown in Fig. 2 were performed under the following conditions: (a) only a thrust magnet is attached; (b) only a radial magnet is attached; (c) both thrust and radial magnets are attached to the rotor.

Fig. 1 Schematic view of a superconducting bearing

Fig. 2 Schematic drawing of an apparatus to measure static properties of a thrust bearing

Fig. 3 Schematic drawing of an apparatus to measure static properties of a radial bearing

Fig. 4 Plots of force versus distance for a thrust bearing

3. Results of Static Measurements

3.1 Static force measurements of a thrust bearing

Figure 4 shows the plots of force against distance for a thrust bearing. In this figure, the distance is given as the gap between the magnet and the surface of the container of the superconducting stator. Therefore, it should be noted that the real gap is larger. The initial gaps before the cooling (G_s) were (a) 4 mm, (b) 2 mm, and (c) 1 mm. The stroke amplitude was 4 mm.

It should be noted that the repulsive force of the first stroke is different from those in the succeeding strokes, and is dependent on the initial gap. It is also notable that the hysteresis loops in the force versus distance plots are almost the same in all the cycles except for the first stroke. These results are explainable by considering the magnetic properties of type II superconductors.

When a magnetic field is applied to the superconductor, the induced currents (J) flow according to the following equation:

$$\text{rot } B = \mu_0 J$$

where B is the magnetic induction, and μ_0 is the permeability of free space. In the case of the critical state, J becomes equal to J_c , and therefore the repulsive force is proportional to $J_c B$.

Figure 5 shows schematic representations of the magnetization process of a pinned type II superconductor. When the field strength exceeds the lower critical field, it can penetrate into the superconductor with a field gradient of $dB/dx = \mu_0 J_c$, as schematically drawn in Fig. 5(a). Here the hatched area corresponds to the diamagnetic component. Therefore, a large diamagnetic property or a repulsive force is attainable when the J_c value is large. Figure 5(b) corresponds to the process where the external field is increased, or the gap between the superconductor and the magnet is decreased. Once the field is decreased, the magnetization is changed to the state as schemati-

Fig. 5 Schematic representation of the magnetization process of a pinned type II superconductor. Figures (a) and (b) correspond to the process where a magnet is moved toward a superconductor, and Figures (c) and (d) correspond to the process where a magnet is moved away from a superconductor

cally shown in Fig. 5(c). It is notable that the field is trapped in this state (the hatched area with a sign of +), which means that both attractive and repulsive forces coexist. When the field is removed, only the attractive component remains, as shown in Fig. 5(d).

In the case of the present study, since the superconductor is cooled with a magnet placed near the superconductor, a certain amount of magnetic field is already present, and the initial state should be modified. Figure 6 shows the schematic diagram for such a state. Here the initial condition is given in Fig. 6(a), where H_0 is the initial magnetic field and depends on the initial gap. When the magnet is moved toward the superconductor, the external field, to which the superconductor is subjected, increases and the magnetization can be schematically drawn as shown in Fig. 6(b). This state corresponds to the initial curve, and therefore, when the initial gap is small or H_0 is large, the maximum force becomes

Fig. 6 Schematic representation of the magnetization process of a superconducting stator in the present study

small, which is the case of Fig. 4 (3). As the magnet is moved away from the superconductor, the attractive component appears in the magnetization, as shown in Fig. 6 (c), which dramatically reduces the repulsive force. When the attractive component becomes equal to the repulsive component, the net force becomes zero. After passing this point, the force becomes attractive, and remains attractive. In this state, a certain amount of field is trapped by the superconductor, as shown in Fig. 6(d), and therefore the state is different from the initial one. As we successively move the magnet toward the superconductor, the repulsive component appears again; however, the magnetization is rather complicated compared to that of the initial curve (Fig. 6(b)), and is given by Fig. 6(e) and Fig. 6(f). When H_0 is small, magnetization at zero gap is the same as that of the initial process. On the other hand, when the H_0 is large, the initial magnetization is smaller than that of the succeeding process. It is also clear that except for the first process, magnetization follows the same process, and therefore, the hysteresis loops are the same, which is consistent with the results given in Fig. 4.

These results suggest that in order to increase the repulsive force, the initial gap should be large. It is also important to note that the force-displacement characteristics of a simple thrust bearing can be understood in terms of magnetization processes of the superconductor.

3.2 Force measurements for three kinds of bearings

3.2.1 Repulsive and attractive forces Figure 7 shows plots of force versus displacement for three kinds of bearings: (a) thrust; (b) radial; and (c) combined bearings with an initial gap of 1 mm. Here the origin is the initial point, the distance is the abscissa, and the repulsive force is the ordinate.

It is clear that the attractive force is larger than the repulsive force for the present superconducting bearings when the initial gap is 1 mm. It is also

Fig. 7 Plots of force versus displacement for three kinds of bearings: (a) thrust; (b) radial; and (c) combined bearings

Fig. 8 Plots of stiffness versus distance for three kinds of bearings with an initial gap of 1 mm

important to note that the combined bearing exhibits the largest force.

3.2.2 Stiffness Figure 8 shows plots of

stiffness as a function of distance for three kinds of bearings when the initial gap is 1 mm. The stiffness was obtained from the gradient of force-displacement curves at a given distance by measuring the gradient of a minor loop. Because of hysteresis, the stiffness takes different values in approaching and removing processes. It is notable that the static stiffness is independent of the gap in the approaching process, where no attractive component exists. On the other hand, when the attractive force acts, the static stiffness depends on the gap. This is explainable by the fact that the attractive component is due to a trapped field, which is mainly responsible for the stiffness.

3.2.3 Force-displacement characteristics in a radial direction Figure 9 shows the force versus displacement in a radial direction for the three kinds of bearings with an initial gap of 1 mm. Here the x -axis represents a displacement from the center of the bearing, and the y -axis is a force which the rotor is subjected to. The radial gap between the rotor and the stator is 2 mm.

The force-displacement curves of superconducting bearings can also be qualitatively explained in terms of the magnetization process presented in Fig. 5. When the rotor moves from the center, the external field, which the superconductor feels, will change such that the force becomes repulsive for the region where the gap becomes small, and is attractive for the region where the gap becomes large. Thus the force will act so as to prevent the deviation of the rotor from its center. However, the force-displacement curve is not reversible because of the irreversible magnetization process presented in Fig. 5. It is also notable that except for the first process, the force-displacement curve will be the same.

As in the case of force-displacement measurements for a thrust direction, the radial force is the largest in the combined bearing. However, the thrust bearing showed larger force than the radial bearing.

Fig. 9 Plots of force versus displacement in a radial direction for three kinds of bearings with an initial gap of 1 mm

This is understood by considering the source of the electromagnetic force and the initial conditions. In this study, the initial gap was set at 1 mm. Because of this small gap, the magnetic field trapped by the thrust bearing is large, and consequently the repulsive force in the thrust direction becomes small. However, in order to move the rotor, a large force is necessary because we need to redistribute a large amount of trapped field.

4. Dynamic Characteristics of the Superconducting Bearing

From the static force-displacement measurements, the characteristics of the superconducting bearing can be summarized as follows. Firstly, the force depends on initial conditions such as the gap, and also on the design of the bearing. Secondly, the stiffness or the force in a radial direction is rather weak. Thirdly, the force both in the thrust and radial directions can be improved by combining thrust and radial bearings. Based on these understandings, we designed the superconducting bearing which is schematically drawn in Fig. 10. In this apparatus, a pair of combined bearings is used, where Fe-Nd-B magnets are attached to the shaft to function as thrust and radial bearings when the superconducting stators are cooled by liquid nitrogen. The shaft is 2.4 kg in

Fig. 10 Schematic drawing of the superconducting bearing

Fig. 11. Oscillographic data for the motion of the rotor at the upper and the lower measuring points with the frequency motor driven at 8 200 rpm.

weight, and is rotated by a high-frequency motor. The amplitude of the rotating shaft is measured at two points, which are indicated as upper and lower measuring points in the figure.

4.1 Centering device

In the case of superconducting bearings, it is necessary to set a rotor exactly in the center of the rotation axis before cooling, because magnets embedded in the rotor can be supported at arbitrary positions due to flux pinning. For example, if the rotor is cooled in contact with the stator, it will be fixed there, and noncontact support is difficult to realize. Therefore, we need to have a centering device which can support the rotor in the correct position.

In the present bearing, the centering device has upper and lower parts, as shown in Fig. 10. The lower part consists of welded bellows and a coil spring, and functions as an air cylinder, which allows a 0-to-4 mm gap for the rotor to move. The rotor is moved upward by using this lower centering device and is centered by making contact with the upper part. The superconducting stator is cooled in this state, and the rotor is supported in this position by flux pinning. When the centering device is released, the rotor moves downward to the position where the force is equal to the weight of the rotor. Thus the rotor is suspended in midair with its rotation axis fixed right at the center of the bearing.

4.2 Critical rotational speed

The centering device also has a pair of mechanical ball bearings, which contribute to another beneficial function, namely, overcoming the critical rotational speed. As mentioned before, the stiffness of the superconducting bearing is rather small, and therefore its first critical point lies at around a few thousand rpm. If the rotor is supported only by the superconducting stator, it is difficult to exceed this critical speed.

Fig. 12. Oscillographic data for the motion of the rotor at 33 000 rpm.

In order to solve this problem, the bearing is first rotated using the centering device or the mechanical ball bearing, and when the rotational speed exceeds the critical speed, the rotor is released and supported in midair, which enables us to rotate the superconducting bearing at very high speed safely.

4.3 Results of rotation test

Figure 11 shows oscillographic data for the motion of the rotor at the upper and lower measuring points with the high frequency motor driven at 8 200 rpm. Figure 11(a) gives the result before the centering device is released, and therefore corresponds to the characteristics of the mechanical ball bearing, while Fig. 11(b) gives the result after the centering device is released, which corresponds to the characteristics of the superconducting bearing.

It should be noted that the rotational speed changes from 4 317 to 8 000 rpm after releasing the centering device. This is evidence that the supporting system is changed from a contact to a noncontact

state.

With noncontact support by the superconductors, the rotational speed could be increased up to 33 000 rpm. Figure 12 shows an oscillographic diagram for the motion of the rotor at this speed. From these data, we see that the rotor is in whirling motion with a relatively long period. This motion is tentatively attributed to a difference in the rotational speed between a rotor and a high-frequency motor. Since the stiffness of the present superconducting bearing is not large, the motion of a rotor will be directly influenced by the difference in rotational speed. As a result, a whirling motion is observed at the frequency corresponding to this difference, and hence this whirling will be suppressed by increasing the stiffness.

5. Conclusions

It was found from the force measurements for various types of superconducting bearings that the force strongly depends on the initial positioning of a magnet and a superconductor, and both the stiffness and the force can be improved by using a combination of thrust and radial bearings.

Based on these understandings, a practical superconducting magnetic bearing was designed and constructed. In this bearing, the function of the centering

device was indispensable, being the support of the rotor in the center of the bearing until the critical speed of the system is exceeded. Using this technique, a 2.4 kg rotor could be rotated up to 33 000 rpm. However, a whirling motion of the rotor was observed, which will be overcome by increasing the stiffness.

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