The Application of Bulk YBaCuO for a Practical Superconducting Magnetic Bearing

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ABSTRACT

We have succeeded in the development of a superconducting magnetic bearing in which a rotor weighing 2.4kg can rotate at 30,000 rpm.

A pair of the superconductor YBaCuO rings (ϕ40 ×ϕ65 ×t20) which were made by Melt-Powder-Melt-Growth (MPMG) process were fixed in the bearing and cooled with liquid nitrogen.

Although most research groups have used the repulsive force between the superconductor and a magnet in the construction of superconducting bearings, we used the attractive force due to flux pinning in this accomplishment. The use of the attractive force enabled us to construct the non-contact bearing, which can be used in a limited space.

Although, the amplitude of vibration in the superconducting bearing was 120μm peak to peak at 30,840rpm, we believe that it is possible to reduce the value by increasing the radial stiffness with some modification in bearing design.

1.Introduction

Since the Y-Ba-Cu-O superconductor with a critical temperature above the liquid nitrogen was discovered in 1987 [1], many industrial, governmental and academic research organizations joined the R&D race. At the time the media speculated that superconductivity applications might become possible at liquid nitrogen temperature or even at room temperature in the very near future.

At the present , although the excited mood that once prevailed has disappeared, research and development work is being carried out in various fields such as in magnetic levitation[2], electromagnetic propulsion ships, and superconducting generators.

While one of the most attractive properties of the superconductor is resistanceless current, the response of the superconductor to magnetic field is also attractive for some applications. In low magnetic fields below H_{c1}, type II superconductors can prevent magnetic flux penetration absolutely, which is known as the Meissner effect. However, the levitation force due to the Meissner effect is small, which limits the application of device. On the other hand, a levitation force can also be obtained in high magnetic fields (above H_{c1}), when the superconductor exhibits pinning force as schematically shown in

Figure 1. Although the external field enters the superconductor, the internal field has a gradient corresponding to

$$dH/dx=Jc$$

,where H is the magnetic field in A/m and Jc is the critical current density in A/m^2. Therefore, the external field H can penetrate into the superconductor by the distance of H/Jc, indicating that the higher is Jc, the larger is the repulsive force.

Murakami et al [3]. have succeeded in dispersing fine non-superconducting particles (Y_2BaCuO_5) in melt processed $YBa_2Cu_3O_x$ and achieved a Jc value exceeding $15{,}000A/cm^2$ at 77K and 1T [4]. Fujimoto et al. achieved $30{,}000A/cm^2$ at 77K and 1T in the Melt-Powder-Melt-Growth (MPMG) method [5]. An increase in a Jc value is attributed to enhanced flux pinning due to the presence of Y_2BaCuO_5 (211) particles, which are expected to work as effective pinning centers. Because of the enhanced flux pinning, the levitation force against the magnet was increased drastically.

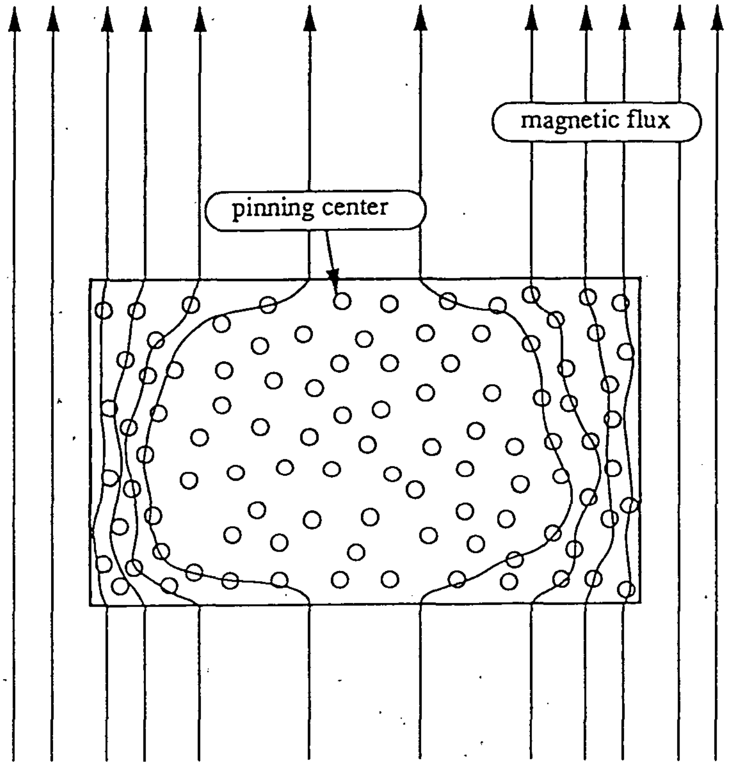


Figure 1. Schematic illustration of magnetic repulsion by flux pinning centers

We fabricated large bulk pieces of the YBaCuO superconductor by the MPMG method and constructed the bearing using these bulk pieces.

In this paper, we first describe the repulsive force between the superconductor and the magnet. Second the process of the large bulk YBaCuO superconductor is introduced. Finally we will report how we constructed the bearing using these bulk pieces.

2. Levitation force of the superconductor

The levitation force F can be written as

$$F=m\ dH/dx$$

,where m is the magnetic moment of the superconductor and dH/dx is a field gradient produced by a magnet. m is equal to Mv where M is the magnetization per unit volume and v is the volume. dH/dx is a constant provided we use the same magnet, while M is dependent on Jc and the size of the shielding current loop according to the follow relation,

$$M=A\ Jc\ r$$

,where A is a constant which depends on sample geometry and r is the radius of the shielding current loop. This size dependence of M is a characteristic of the superconductor and is the key to large levitation force.

In order to increase F, we must increase either Jc or r. In most high Jc samples, r is not proportional to sample size, and the shielding current is localized in individual grains, since most gain boundaries act as weak-links. It is possible to fabricate Y-Ba-Cu-O samples consisting of grains with diameter greater than 1cm using the MPMG process. which can contribute to an increase in r.

If we use the same superconductors, the levitation force is influenced by the size of superconductors and also the size and the strength of the magnet. Figure 2 shows the levitation force of MPMG pellets 1.7 cm in diameter against 0.4 T magnet 1.2 cm in diameter as a function of the thickness of the pellets. The force increases with increasing the thickness and seems to saturate. Therefore it is necessary to fabricate large bulk YBaCuO for practical application.

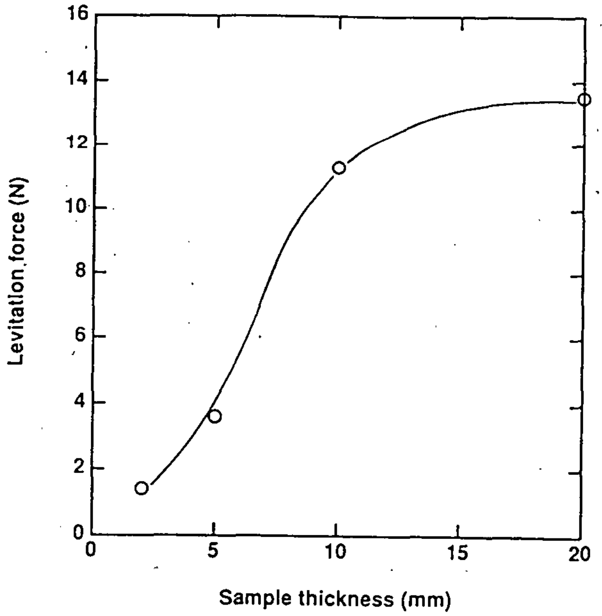


Figure 2. Levitation force of MPMG pellets as a function of the thickness of the pellets

3. Large bulk superconductor

3-1. Process

Large bulk superconductors were prepared by the MPMG process. A schematic illustration of the MPMG process is presented in Figure 3. Appropriate amounts of mixtures of Y_2O_3 ,$BaCO_3$ and CuO were calcined at 920 °C , then the powders were melt at 1,400 °C and rapidly cooled down to room temperature. After the melt oxides were pulverized and added $10_{wt\%}$ Ag_2O and then pressed into pellets approximately 7.4cm in diameter and 2.7cm in thickness. If we press them uniaxialy, they crack during the process. To avoid cracking, we used the method of cold isostatic pressing. The pellets were reheated to 1,100 °C and cooled slowly to room temperature. At the final stage, the pellets were annealed at 600°C and cooled down to room temperature in flowing oxygen. Final dimension of the pellet was 6.7cm in diameter and 2.4cm in thickness, weighing 500g and it had no cracks.

Superconductive materials could be machined into rings by grinding in high precision with dimensions of $\phi 40 \times \phi 65 \times t$ 20mm. The hole 40mm in inner diameter could also be drilled without introducing cracking.

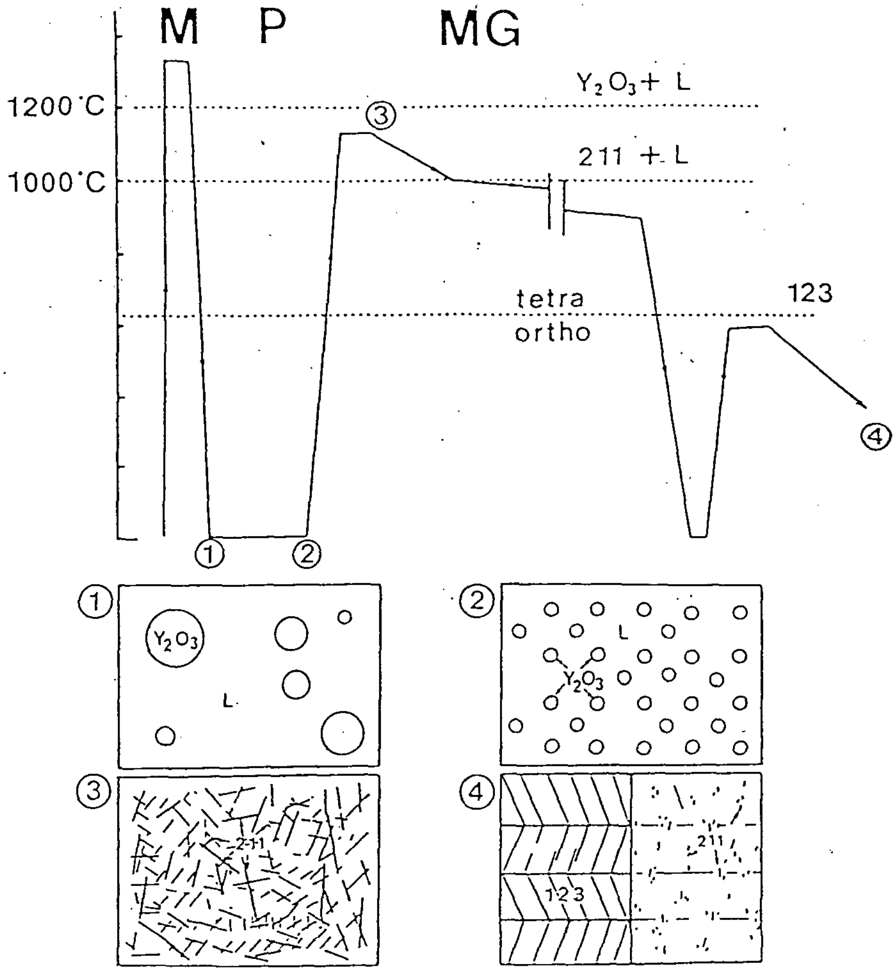


Figure 3. Schematic illustration of MPMG process

3-2. Characterization

Figure 4 shows an optical microgragh and a transition electron micrograph of the MPMG sample. It is notable that the distribution of the 211 particles is very fine and uniform. The 211/123 interface is also very clean and sharp. These 211 particles are expected to work as effective pinning centers [6].

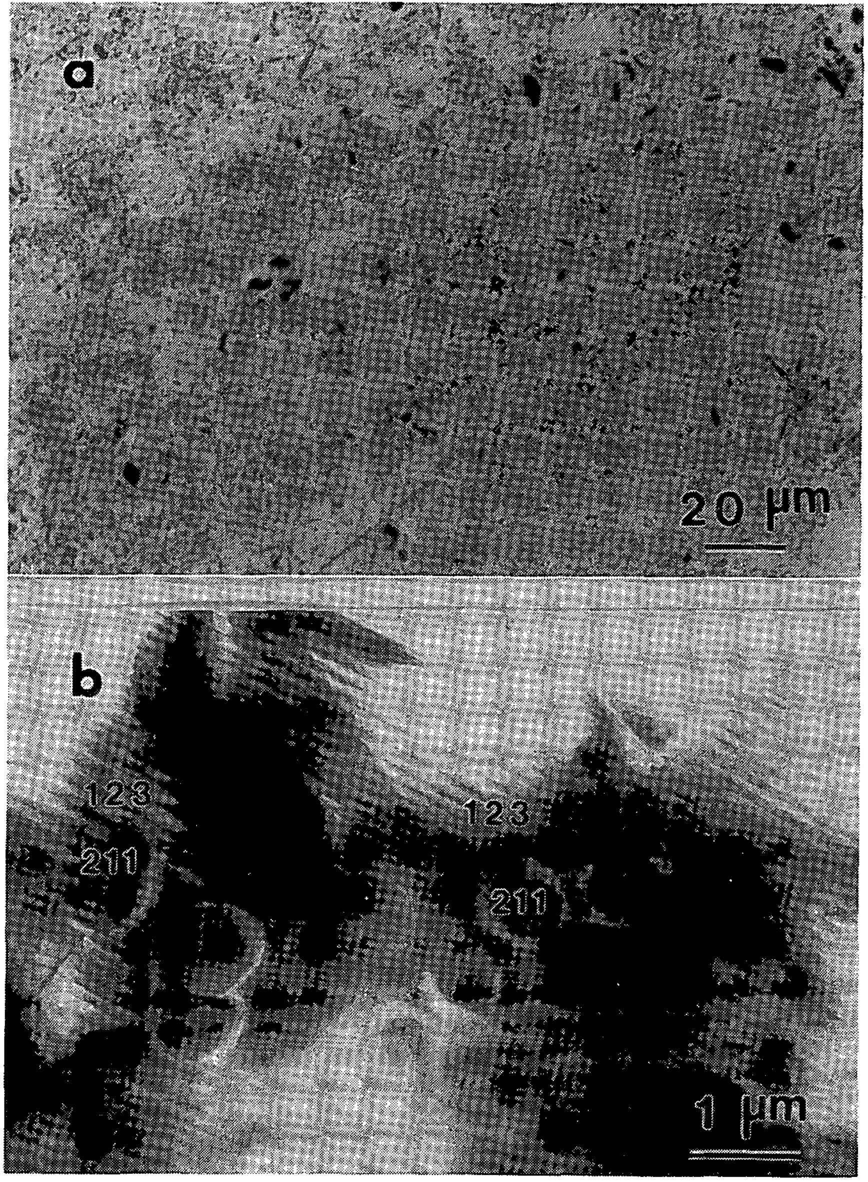


Figure 4. (a) optical microgragh and
(b) transition electron micrograph of MPMG sample

3-3. Levitation force

The repulsive forces between a magnet and bulk MPMG YBaCuO cooled by liquid nitrogen were measured. The size of magnet (Nd-Fe-B) is 7.2cm in diameter, 7.5cm in thickness and the flux density of the surface is approximately 4,500gauss. The repulsive force was approximately 130N.

4. Superconducting magnetic bearing

4-1. Design

The structure of the bearing is shown in Figure 5. A pair of superconducting bearing components were fixed in two places axially separated from each other in the rig. These superconducting bearing components attract and repel the magnets attached to the rotor shaft when they are cooled by liquid nitrogen.

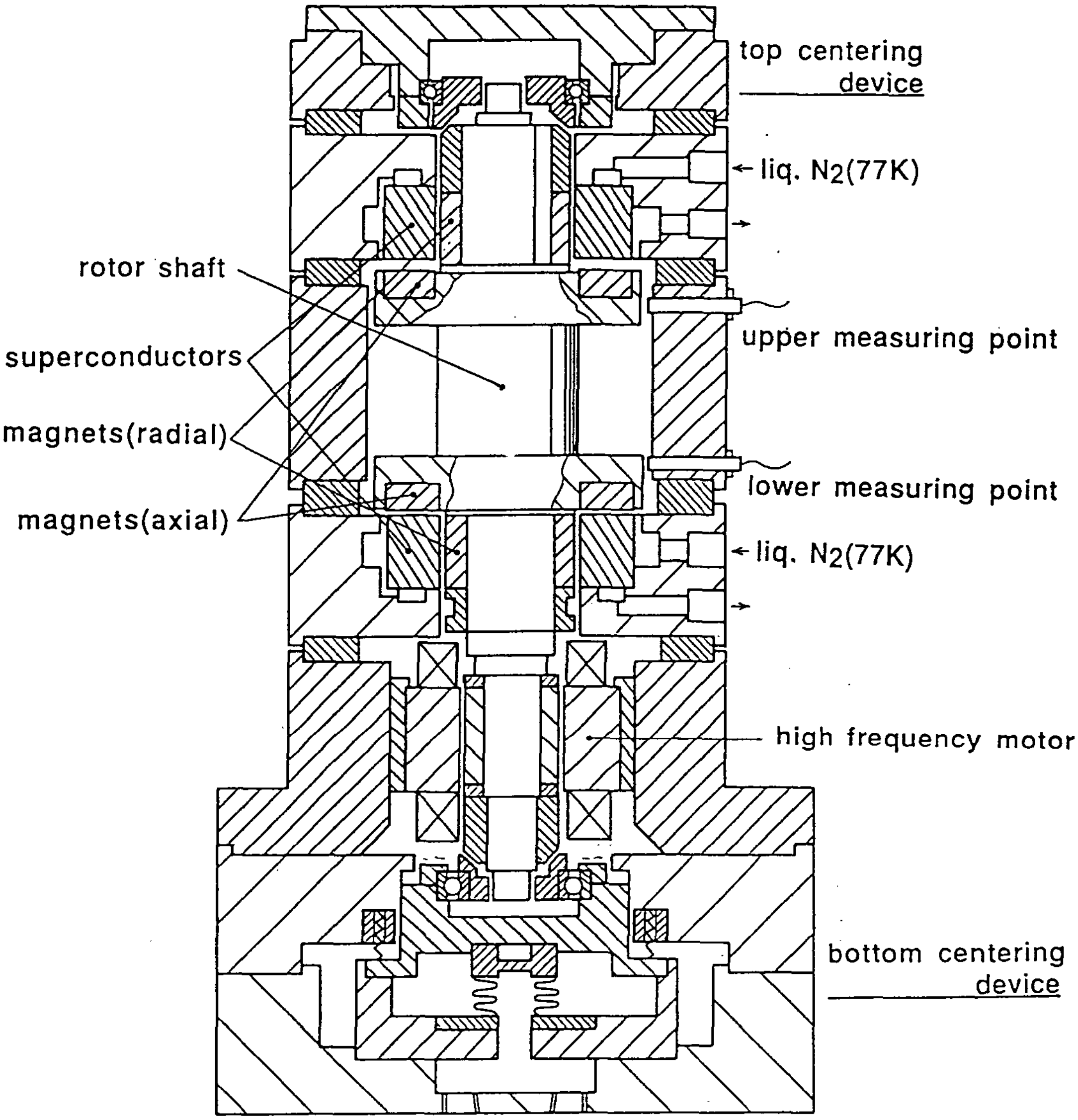


Figure 5. Superconducting magnetic bearing

Centering devices were set at the top and bottom of the rig. The shaft was rotated by a high frequency motor. Radial displacements of the shaft were measured both at the upper and the lower measuring points in X-Y directions as shown in Figure 5.

The characteristics of this bearing are as follows:

(1) Centering device was provided for centering the shaft resulting in perfect non-contacted levitation for high speed rotation beyond the critical speed of the bearing system.

(2) Superconductor rings were set in the spaces partitioned with thin sealed plates and were cooled by circulating liquid nitrogen.

(3) Thin film of epoxi resin was coated over the superconductor rings so as to prevent deterioration of superconductor due to frost during cooling and heating cycles.

(4) Using two superconductors and two sets of magnet rings, the rotating shaft was driven by a high frequency motor.

The dimension of the superconducting magnetic bearings is shown in Table 1.

Table 1. Dimension of superconducting magnetic bearing

superconductor	$\phi40\times\phi65\times t20$
magnet	
for axial bearing	$\phi40\times\phi65\times t\ 8$
for radial bearing	$\phi36\times\phi25\times t20$
seal plate	
inner diameter	$\phi38$
thickness	0.6mm
clearance	
radial of magnetic	2.0mm
radial of touch-down	0.35mm
axial of magnetic	6.5mm
axial of touch-down	5.5mm

A photograph of the superconducting bearings and the shaft is shown in Figure 6, and the outlook of this bearing apparatus is shown in Figure 7.

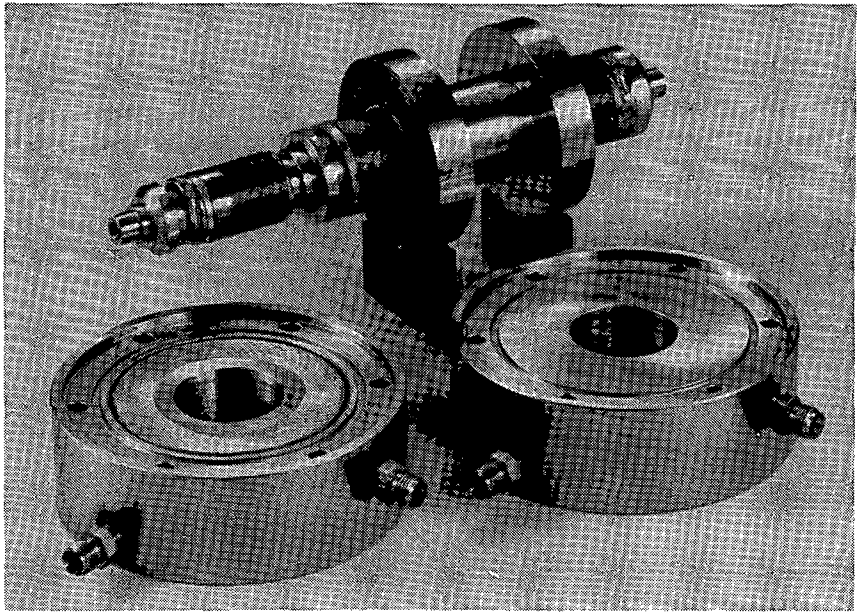


Figure 6. Superconducting bearing component and rotor shaft

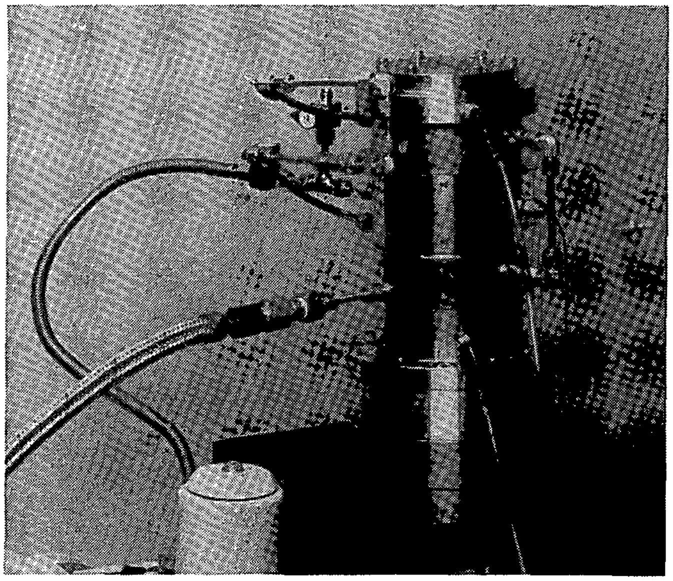


Figure 7. Entire view of the bearing

4-2. Centering device

The structure and operation of the centering device are described in more detail below.

Under field cooling, the centering device is needed in order to settle the rotor shaft in the right position. Otherwise, superconducting bearings would fix the rotor shaft at arbitrary position by flux pinning when it was cooled. In this case, superconducting magnetic bearings cannot operate at perfect non-contact rotation.

The centering device consists of a top centering part and a bottom centering part as shown in Figure 5. The bottom centering part has an air-cylinder function which consists of bellows and coil springs, and it could move the shaft up and down within the span of 4mm. The shaft was pushed up to the top centering part and becomes centered.

Under centered condition, the shaft was rotated and supported by ball bearings over the critical speed of the bearing system, and then the superconducting magnetic bearings were cooled by liquid nitrogen.

In this state, air pressure of lower centering part was released. The shaft fell down to the position where the axis load capacity of superconducting magnetic bearings was equal to the shaft weight, and rotated without contact. In this case, the levitation force was mainly due to the attractive force. That is, the suspension of this bearing apparatus was carried by not only the repulsive force but also the attractive force.

The tapered inner rings of the centering device also play a role of touch down bearings in the case of high speed rotation.

4-3. Experimental results

Tests were carried out with the rotation speed of more than 30,000 rpm. The results of run tests are shown in Figure 8 to 10. Figure 8 shows the amplitude of vibration versus rotational speed of the first and second experiments. In the first experiment, the amplitude became nearly constant 120 μm peak to peak at upper measuring point beyond 11,000 rpm. In the second test, the amplitude became minimum at 16,000 - 18,000 rpm both at upper and bottom measuring point. Beyond 26,000 rpm, the amplitude reached nearly constant 120 μm peak to peak at upper measuring point and nearly constant 75 μm peak to peak at bottom measuring point.

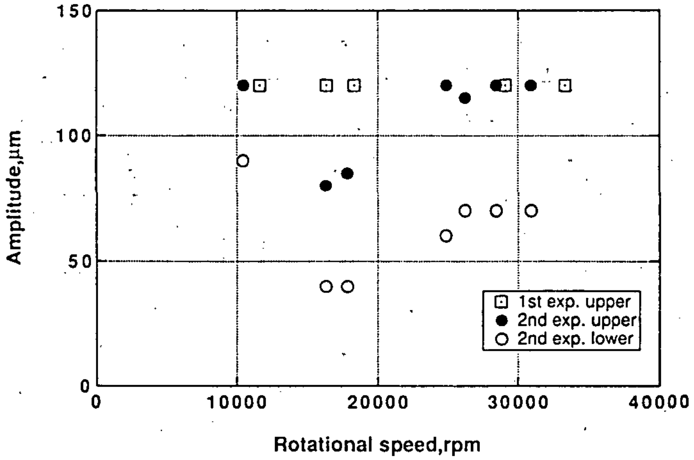
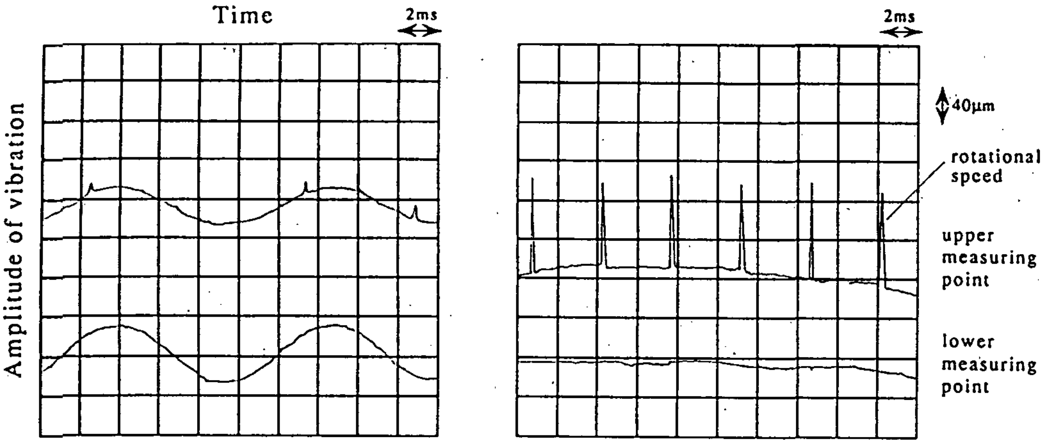


Figure 8. Run out with rotational speed

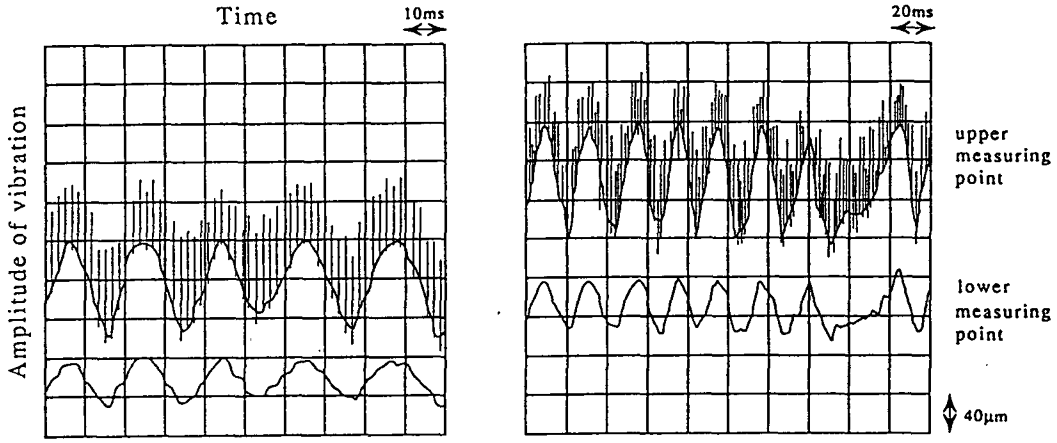
Figures 9 and 10 show the oscillograms of vibration of the shaft in the second test. Figure 9 shows the rotational speeds before and after releasing the function of centerizing device. Figure 9 (a) is when the centerizing device was acting and the shaft was supported by ball bearings. In Figure 9 (a), the setting speed of high frequency motor was about 8,100 rpm, and actual speed of the shaft was 4,317 rpm. Figure 9 (b) is when the centering device was set free and the shaft was levitated in perfect non-contact state by superconducting magnetic bearings. Rotational speed increased rapidly from 4,317 to 8,000 rpm. This assures that supporting situation changed from ball bearing support with large friction to superconducting magnetic bearing support with low friction.

Figure 10 shows the displacements of shaft and the pulses of rotation at (a) 17,700 rpm and (b) 30,840 rpm. The shaft was found rotating in whirling motion with an amplitude of 120 µm peak to peak with 1/5 - 1/7 period of shaft rotation. The phase of whirling motion was the same at the upper measuring point and the lower measuring point, so the whirling motion was in cylindrical motion. At present, it is not clear whether this long whirling period is due to high frequency motor or due to native characteristics of superconducting magnetic bearings.



(a) 4,317 rpm (b) 7,999 rpm

Figure 9. Increase of rotational speed
(a) with rolling bearing
(b) superconducting magnetic bearing alone



(a) 17,700 rpm

(b) 30,840 rpm

Figure 10. Experimental record at high speed

5. Conclusions

It has been proved that YBaCuO superconductors fabricated by the MPMG process can be produced in large size (ϕ67 × t 24) without cracking. They had very fine and uniform 211 particles which are expected to work as effective pinning centers, so their levitation force against the magnet was very strong (over than 130 N). And they can also be applied to precise machining to make rings without deteriorating their superconducting properties.

The superconducting magnetic bearing with a structure similar to a conventional magnetic bearing, utilizing large repulsive and attractive forces due to flux pinning between MPMG-YBaCuO superconductors and magnets enabled a 2.4 kg shaft to rotate safety at over 30,000 rpm.

6. Reference

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