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To cite this article: R Okamura *et al* 2017 *J. Phys.: Conf. Ser.* **871** 012096

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# Study on the Rotation Properties and the Design Issue of Non-Contact Rotating System Using HTS Bulks and Permanent Magnets

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**Abstract.** In previous study, non-contact rotating system consisting of the ring-shaped high temperature superconducting (HTS) bulks, ring-shaped permanent magnets (PMs) and stator coil was proposed. In this system, HTS bulks were magnetized by PMs and PMs were levitated with strong restoring force. In our previous study, we have constructed the rotating system with the ring-shaped HTS bulks with ID 20 mm, OD 60 mm, and 15-mm thickness. However, since these bulks costs too much, we switched to use HTS bulks with ID 20 mm, OD 60 mm, and 5-mm-thickness to miniaturize the system. However, this system have potential to fail the radial stability of rotating shaft. Therefore, we focused on the rotating and the radial restoring force in terms of the stability of the rotating shaft in the rotating system with 5-mm thickness HTS bulks.

## 1. Introduction

The application of non-contact levitation technology has advantages such as no energy loss and easy maintenance because of no mechanical friction. For these reasons, the non-contact levitation technologies using electrostatic force, ultrasonic wave, air pressure, electromagnetic force have been studying. Particularly, the technology using electromagnetic force has the advantages such as a large levitation force and easy handling.

The HTS bulks magnetized by field cooling (FC) method[1][2] show both diamagnetic behavior and pinning effect. By using these characteristics, the PMs can be levitated with stability[3]-[6]. From our previous study, it is known that our system using ring-shaped PMs and ring-shaped HTS bulks is very useful to apply to the non-contact rotating system. The maximum rotating speed of 840 rpm was obtained in the non-contact rotating system by using the ring-shaped HTS bulks with ID 20 mm, OD 60 mm, and 15-mm thickness[7]. However, since it costs too much, we switched to use HTS bulks with ID 20 mm, OD 60 mm, and 5-mm-thickness to miniaturize the system. However, it is predicted that the radial stability of rotating shaft will be weakened. Therefore, we studied about the rotating and the radial restoring force in terms of the stability of the rotating shaft using 5-mm-thickness HTS bulks.

## 2. Rotating system and experimental details

### 2.1. Rotating system and experiment

The proposed non-contact rotating system is shown in Figure 1. Table 1 shows the specifications of components used in the experiments. Figure 2 (a) and (b) show the measurement results of magnetic field distribution for surface of PM(1) and 12 mm above the surface of PM(1) respectively. PM (1)

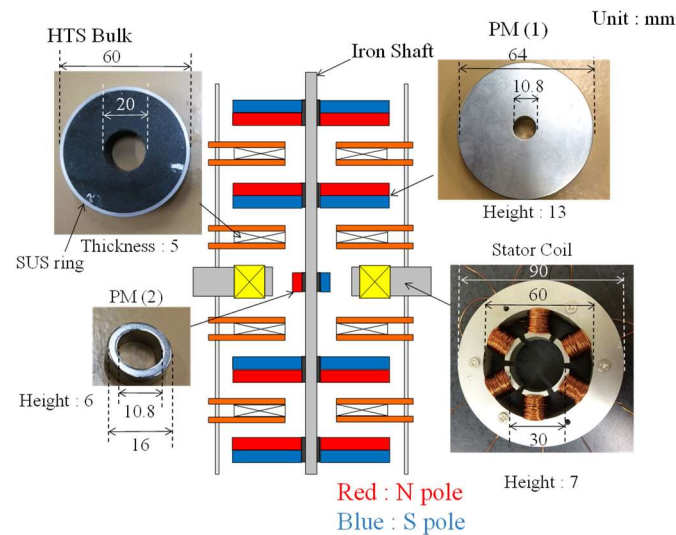


magnetized in the axial direction was used to increase the axial restoring force of the rotating shaft in the system. Furthermore, two PM (1)s are faced and arranged on the opposite side of HTS bulk in order to increase the radial restoring force. PM (2) for the rotor of motor is the permanent magnet attached to iron shaft and PM (2) is multi-poles magnet which generates a magnetic field in the radial direction. Figure 3 (a) and (b) show measured area of magnetic field distribution around PM(2) and measurement result of magnetic field distribution for PM(2) respectively.

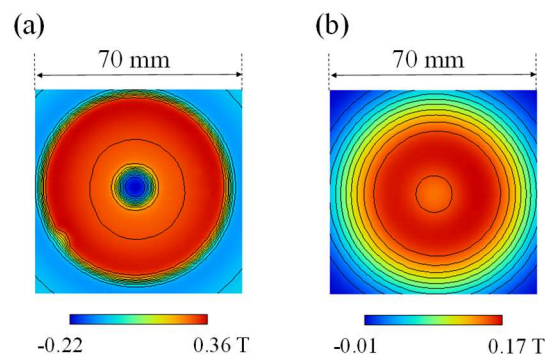
The HTS bulks were magnetized by PM (1)s with FC method with liquid nitrogen. Therefore, PM (1)s were levitated because of the trapped HTS bulks with pinning force. The iron shaft with PM (1) and PM (2) is rotated by applied current to the stator coil using three bipolar amplifiers.

**Table 1.** The specifications of components used in the experiments

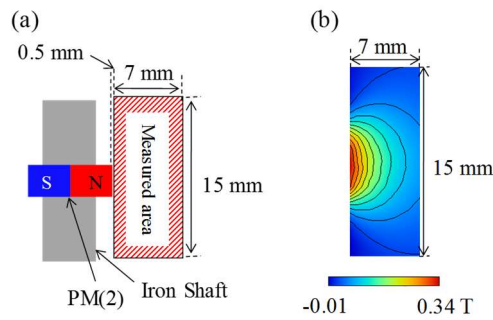
	Inner diameter (mm)	Outer diameter (mm)	Height (mm)
HTS Bulk	20	60	5
PM (1)	10.8	64	13
PM (2)	10.8	16	6
Stator coil	30	90	7



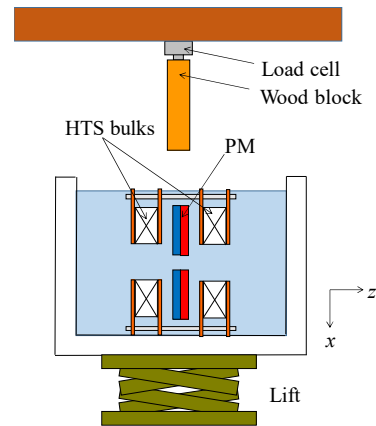
**Figure 1.** Schematic drawing of proposed the non-contact rotating system and photos of the ring-shaped HTS bulks, 2 types PMs and stator coil.



**Figure 2.** The measurement results of magnetic field distribution, (a) surface of PM(1) and (b) 12 mm above the surface of PM(1).



**Figure 3.** (a) Measured area of magnetic field distribution around PM(2) and (b) Measurement result of magnetic field distribution for PM(2).



**Figure 4.** The measuring method of radial restoring forces in the radial directions.

## 2.2 Experiment of radial restoring force

Figure 4 shows the measurement method of a radial restoring force. The HTS bulks magnetized by field cooling (FC) method show both diamagnetic behavior and pinning effect. The HTS bulks and permanent magnet are magnetically coupled. Then, the PM has the force to stay in the initial position. The HTS bulks were magnetized by PM with FC method, and PM levitated between HTS bulks. Then, we measured the radial restoring force against the displacement from the levitating position by using load cell. And we also measured the radial restoring force when the thickness of HTS bulks are 5 mm and 15 mm, and the several levitation systems were designed and tested experimentally.

## 3. Results and discussion

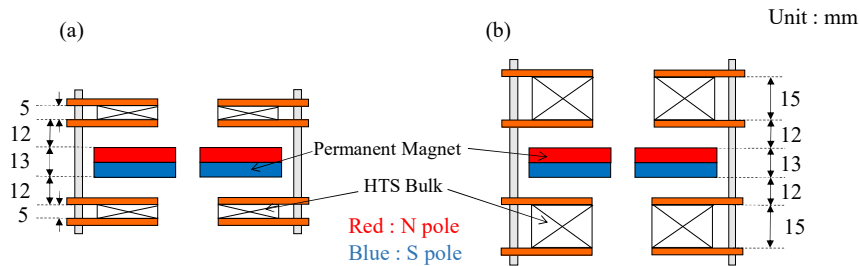
In general, the restoring force of proposed rotating system is increased according to increasing the thickness of HTS bulk. So, the thick HTS bulks are very effective for improving the restoring force, and 15-mm thickness HTS bulks were used in our previous study [7]. However, the cost of HTS bulk increases in proportion to its thickness. Therefore, we tried to reduce the thickness of HTS bulks (from 15 mm to 5 mm) used for our rotating system. Firstly, rotating test with the system as shown in Figure 1 were carried out. However, when the rotating system was levitated with FC method, PM(2) as the rotor was adsorbed by the stator coil and could not rotate because the radial stability of the rotating shaft was weakened by changing the HTS bulks with thickness of 15 mm to those with thickness of 5 mm in the rotating system. Therefore, we estimated the radial stability of the rotating shaft by measuring the radial restoring force using 1 unit levitation system with 15-mm and 5-mm thickness HTS bulks as shown in figure 5.

### 3.1. Radial restoring forces

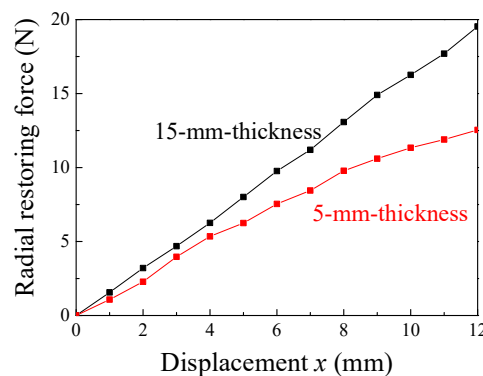
**3.1.1. The comparison by thickness of HTS bulks** HTS bulks with a thickness of 15 mm have been used in the previous study. However, in this study, HTS bulks with a thickness of 5 mm have been used. Hence, we compared radial restoring force using 5-mm-thickness HTS bulks and 15-mm-thickness HTS bulks. Figure 5 shows the schematic drawings of the levitation systems (here in after referred to as “1 unit system”) without shaft in this experiment.

Figure 6 shows the measurement results of radial restoring forces for 1 unit system without shaft. As seen in figure 4, the restoring force for the system with 15-mm-thickness HTS bulks is larger than that

with 5-mm-thickness HTS bulks. This difference of the restoring force is related to the HTS bulks thickness. The amount of trapped magnetic field is larger in a wider range with the larger thickness of the bulk, and the larger restoring force works on the HTS bulk. Hence, we need to consider new structure of the levitation system using 5-mm-thickness HTS bulks.



**Figure 5.** The schematic drawings of the 1 unit levitation system for the measuring radial restoring forces. (a) Using 5-mm-thickness HTS bulks and (b) Using 15-mm-thickness HTS bulks.



**Figure 6.** Measured radial restoring forces in 1 unit system using HTS bulks with thicknesses of 5 mm and 15 mm).

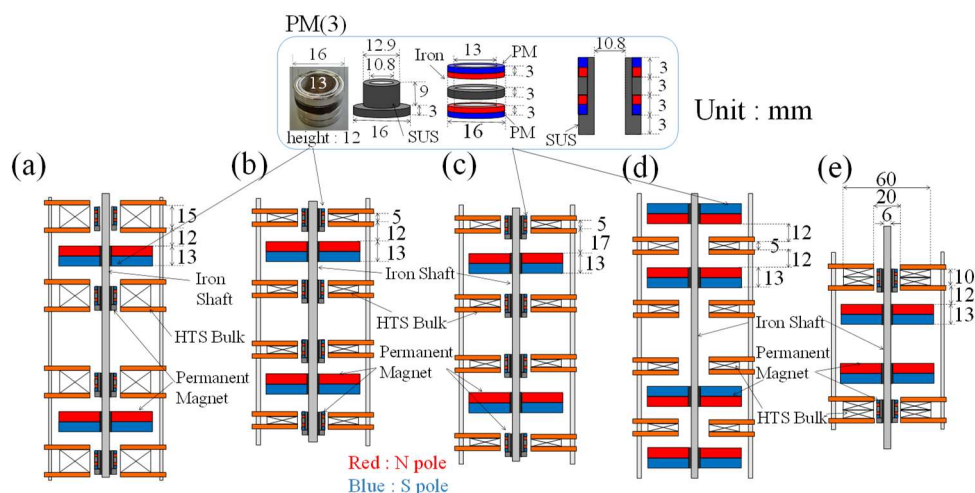
**3.1.2. The comparison by design of the levitation system** To improve the restoring force in the radial direction, the high magnetic field strength and the large magnetic gradient in the radial direction are necessary, and thick HTS bulks are very effective for improving the restoring force. Therefore, we investigated the system structure which can obtain a high restoring force even though using a thin HTS bulk.

Figure 7 shows the schematic drawings of the cross-sectional structure of several levitation systems in the experiments. Figure 7(a) shows a levitating system used in measuring the rotation characteristics in our previous study using 15-mm thickness HTS bulks, and the stator coil was removed to measure the restoring force. Figure 7(b) is the same structure shown in figure 7(a) except that the thickness of HTS bulks is changed from 15 mm to 5 mm. Figure 7(c) basically has the same structure as figure 7(b), but the distance between PM(1) and HTS bulk is expanded from 12 mm to 17 mm in order to reduce the influence by PM(1) against PM(3). In figure 7(d), PM(1)s are arranged face to face with the same polarity at both sides of HTS bulk in order to improve the strength of magnetic field applied in radial direction of HTS bulk (here in after referred to as “4 PMs + 4 Bulks system”). Then, in order to obtain

the levitation force in the axial direction, two HTS bulks were placed at the center part of the rotating shaft. In order to confirm the influence by the thickness of HTS bulk, two HTS bulks with 5 mm thickness were stacked as shown in figure 7(e) (here in after referred to as “2 PMs + 2 Bulks system”).

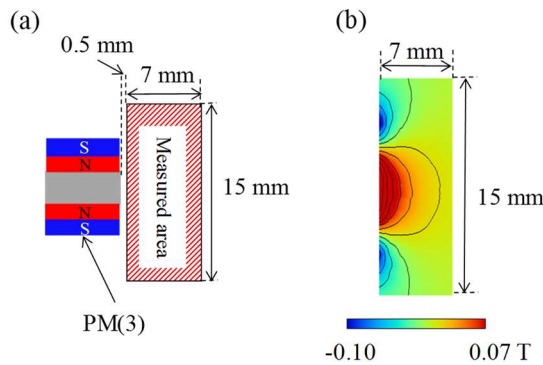
Figure 8 shows the measuring area at near the PM(3) and measured the magnetic field distribution around PM(3). In order to increase the restoring force in the radial direction, the PM(3) has a structure which two ring-shaped PMs were combined with opposite direction, and the iron ring was sandwiched by PMs for increasing the magnetic flux in the radial direction. These PM(3)s are directly attached to the rotating shaft and placed in the inner part of the HTS bulks.

Figure 9 shows the measurement results of radial restoring force for the various levitation systems. 4PMs + 4Bulks system and 2 unit system using 5-mm-thickness HTS bulks did not obtain enough radial restoring force to be measured. These systems fell down and contacted inside HTS bulks trying to levitate them horizontally. This is because by using 5-mm-thickness bulks, the range in which the magnetic field generated by PM (3) as shown in figure 8 can be captured is smaller than in the case of using 15-mm-thickness bulks. Therefore, the radial restoring force became smaller by using 5-mm-thickness HTS bulks. 2 PMs + 2 Bulks system was able to measure the radial restoring force. Due to using stacked two 5-mm-thickness HTS bulks, the radial restoring force was larger than that using 5-mm-thickness bulks. However, the shaft contacted inside HTS bulks with 1 mm displacement, and the radial restoring force could not be measured any further. Comparing the radial restoring force of 2 PMs + 2 Bulks system and 2 unit system (using 15-mm-thickness HTS bulks), it can be seen that the radial restoring force of the system using stacked two 5-mm-thickness HTS bulks is smaller than that using 15-mm-thickness HTS bulks. As these results, it was found that radial restoring force is insufficient in any case using 5-mm-thickness HTS bulks. Also, the radial restoring force obtained in the model using stacked two 5-mm-thickness HTS bulks is larger than the model using non-stacked bulks. However, the radial restoring force is still smaller than that in the case with 15-mm-thickness HTS bulks, therefore larger radial restoring force is required for a stable rotation. Therefore, we need to consider the design using stacked two 5-mm-thickness HTS bulks.

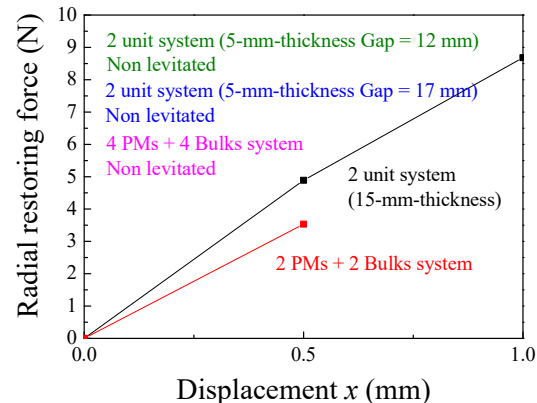


**Figure 7.** The schematic drawings of the levitation system to measure the radial restoring forces and the photo of the PM(3) as bearing. (a) 2 unit system (using 15-mm-thickness HTS bulks), (b) 2 units system (using 5-mm-thickness HTS bulks, Gap = 12 mm), (c) 2 unit system (using 5-mm-thickness HTS bulks, Gap = 17 mm), (d) 4 PMs + 4 Bulks system and (e) 2 PMs + 2Bulks system.





**Figure 8.** (a) Measuring area at near the PM(3) and (b) measured the magnetic field distribution around the PM(3).



**Figure 9.** Measured radial restoring force of the various levitation systems.

#### 4. Conclusion

In previous study, we proposed non-contact rotating system composed of HTS bulks, PMs and stator coil. The proposed non-contact levitation system can be used a rotating machine to apply the medical apparatus such as medical mixer. In order to use the developed levitation system as a rotating machine, the stability of the rotating shaft is very important, and it is necessary to improve the restoring force of the rotating shaft. To improve the restoring force in the radial direction, the high magnetic field strength and the large magnetic gradient in the radial direction of HTS bulk are necessary, and thick HTS bulks are very effective for improving the restoring force. However, the cost of HTS bulk increases in proportion to its thickness. So, we studied to improve the strength of the magnetic field in radial direction of HTS bulk and tried to reduce the thickness of HTS bulks for economic reasons. The measured restoring force in the radial direction using 1 unit levitation system with 5-mm thickness HTS bulk was 30% smaller than that of system using the 15-mm thickness HTS bulk. The several levitation systems for improving the restoring force using 5-mm thickness HTS bulks were designed and tested experimentally. However, the designed levitation models using 5-mm thickness HTS bulks did not levitated, and measured the restoring force of 2 PMs+2 Bulks system was also lower than that of the model using the 15-mm thickness HTS bulk. Therefore, it was confirmed that the thickness of the HTS bulk is very effective in our proposed system. However, we need to continue research for reducing the thickness of the HTS bulk to solve the economic problem due to expensive HTS bulks.

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