A Double-Superconducting Axial Bearing System for an Energy Storage Flywheel Model

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Abstract. The bulk high temperature superconductors (HTSCs) with unique flux-pinning property have been applied to fabricate two superconducting axial bearings for an energy storage flywheel model. The two superconducting axial bearings are respectively fixed at two ends of the vertical rotational shaft, whose stator is composed of seven melt-textured YBa₂Cu₃O₇₋ₓ (YBCO) bulks with diameter of 30 mm, height of 18 mm and rotor is made of three cylindrical axial-magnetized NdFeB permanent magnets (PM) by superposition with diameter of 63 mm, height of 27 mm. The experimental results show the total levitation and lateral force produced by the two superconducting bearings are enough to levitate and stabilize the 2.4 kg rotational shaft. When the two YBCO stators were both field cooled to the liquid nitrogen temperature at respective axial distances above or below the PM rotor, the shaft could be automatically levitated between the two stators without any contact. In the case of a driving motor, it can be stably rotated along the central axis besides the resonance frequency. This double-superconducting axial bearing system can be used to demonstrate the flux-pinning property of bulk HTSC for stable levitation and suspension and the principle of superconducting flywheel energy storage system to visitors.

1. Introduction
Due to the high critical current densities $J_c$ and magnetic irreversibility field $H_{irr}$ at liquid nitrogen temperature, high temperature superconductors (HTSCs), e.g. the typical melt-textured YBa₂Cu₃O₇₋ₓ (YBCO) bulk [1], have been widely used in the field of high temperature superconducting (HTS) magnetic levitation technology. The characteristic of HTS magnetic levitation is that a permanent magnet (PM) can stably levitate above or suspend below a bulk HTSC due to its flux pinning property, moreover, it’s a completely passive levitation system. To explore its levitating characteristic for industry application, many small-scale models and big-scale prototypes using bulk YBCO have been fabricated in rotating machines and linear transportation systems, such as heavy-load superconducting magnetic bearings of ATZ [2] and Nexans SuperConductors GmbH in Germany [3], kWh class flywheel energy storage systems (FESS) of Boeing Company in American [4], ISTEC in Japan [5], ATZ with Magnet-Motor GmbH [6], “DYNASTORE” project in Germany [7], man-loading levitation linear transportations of ASCLab in China [8] and IFW in Germany [9], HTS motor of Siemens AG in Germany [10], HTS launch systems of ASCLab [11] and BUAA in China [12], and so on [13].

Although the HTS magnetic levitation technology has been successfully applied to the above prototypes and demonstrated its tremendous potential, there is still a distance for practical application. The common problems in large-scale applications, especially for FESS, are its relative low load
capability, stiffness and dynamic stability comparing to active magnetic levitation system. Then the concept of hybrid levitations appears to overcome these problems, that is, permanent magnets are added to improve the load capability [4, 6] and electromagnets are added to improve the stiffness and dynamic stability [5]. As to the present performances of HTS materials, the two methods are both effective and available to complement the defects of HTS magnetic levitation system, whereas they will bring some unsafe factors and make the system complicated. However, with the continuous efforts to the bulk HTSC materials [14], it is believed that the load capability, stiffness and dynamic stability of HTS magnetic levitation system can be improved much so that it can satisfy the requirements of industrial applications by itself. Then the whole system will be greatly simplified [7].

From this point of view, a full superconducting bearing system was fabricated for an FESS model which was used to demonstrate HTS energy-saving technologies under the background of increasing energy crisis. The bearing system is composed of two axial type superconducting magnetic bearings (SMBs) owing to its easy fabrication [15], which are respectively fixed at two ends of a vertical shaft. The experimental levitation and lateral force results imply the two axial SMB can completely levitate and stabilize the 2.4 kg shaft. In the case of a driving motor, the rotational shaft can stably rotate along the central axis without any contact except the condition of resonance frequency. The spin-down running experiments show that the system has two obvious resonance rotational speeds where the vibration of the rotor sharply increases. It was further verified by the pulse response experiments.

The feature of the double-axial-SMB system is that the stable levitation and suspension phenomena of bulk HTSC are both displayed at the same time. It can be used to demonstrate the flux-pinning property of bulk HTSC for stable levitation and suspension, the characteristics of SMB and the principle of FESS to visitors.

2. Design

2.1. System description

![Figure 1. Schematic overall view of the double-superconducting axial bearing system](image)

The schematic diagram of the double-superconducting axial bearing system is shown in figure 1. It is a vertical structure, and the total height is 610 mm. The system is mainly composed of three parts: support platform, SMBs and driving module. The support platform is a circular base plate made of epoxy resin with diameter of 500 mm. Four non-magnetic stainless steel screws are fixed on the center of the base plate symmetrically, surrounding into a side length of 200 mm square. They are used to install and position the stators, including two SMB stators at the top and bottom and the motor stator at
the middle. Corresponding to the stators, two SMB rotors are mounted at the two ends of a vertical rotational shaft while the motor rotor is mounted at the middle, as shown in the right part of figure 1. The total weight of the rotational shaft is 2.4 kg. In order to distinguish, the two SMBs are called as upper SMB and lower SMB respectively. The rotational shaft is mounted concentrically between the two SMB stators, at the middle of which an inductive motor with an air gap of 2.5 mm is mounted to drive the SMB to high speed. In addition, a transformer is used to control the rotational speed of the motor by changing the voltage of power supply. The max rotational speed is 3000 rpm.

2.2. SMBs

The two axial SMBs are the heart part of the system, one of which is used to levitate and the other one is used to suspend the rotational shaft. The stators are both composed of seven single-domain melt-textured YBCO bulks with diameter of 30 mm, height of 18 mm (as shown in figure 2) and rotors are both made of three cylindrical axial-magnetized NdFeB PMs by superposition (as shown in figure 3). The each PM is 63 mm in diameter and 9 mm in height, and its max surface magnetic field is 0.4 T.

Two epoxy fiberglass dewars are used as holder and cryostat for the YBCO bulks, as shown in the right part of figure 1 and figure 2. This kind of dewar has many advantages, such as easy fabrication by manual, non-magnetoconductivity, high mechanical strength, low thermal transfer and so on. The two dewars are both with outer diameter of 140 mm, height of 75 mm and the thickness of wall is only 2 mm.

Before applying the two SMBs to the system, the levitation and lateral force performances are investigated respectively. All the maglev measurements are performed on a self-developed HTS maglev measurement system [16].

![Figure 2. Photo of axial SMB YBCO stator](image2.png)

![Figure 3. Photo of axial SMB PM rotor](image3.png)

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![Figure 4. Levitation force curves of upper SMB](image4.png)

![Figure 5. Lateral force curves of upper SMB](image5.png)
The magnetic levitation performances of SMB are directly depended on the field cooling height (FCH) and working height (WH) between the PM rotor and YBCO stator [17]. If the FCH is larger than WH, a repulsion interaction force will be generated between the HTSC and PM. Then at a certain WH, the higher FCH will bring bigger repulsion force but smaller lateral force, and vice versa. If the FCH is less than WH, an attractive interaction force will be generated between the HTSC and PM. Then at a certain WH, the lower FCH will bring bigger attractive and lateral force, and vice versa. The typical curves are similar to that shown in figure 4, 5, 6 and 7, which denote the levitation and lateral force performances of upper and lower SMB respectively.

In order to get a more stable system, the appropriate working condition of SMB was obtained by experiments. As to the upper SMB, the FCH 3 mm and WH 5 mm are chosen, where the upper SMB will generate an attractive force of -15.402 N and a max lateral force of 8.17 N at the max tolerant lateral position of 2.5 mm (as shown in figure 4 and 5). In the case of lower SMB, the FCH 15 mm and WH 5 mm are chosen, where the lower SMB will generate a repulsion force of 39.179 N and a max lateral force of 3.19 N at the max tolerant lateral position of 2.5 mm (as shown in figure 6 and 7). Considering the two SMBs are installed at the two ends of the rotational shaft, the total levitation and lateral force can be obtained by algebraic superposition. So the double SMBs system can provide a levitation force of 54.581 N and a lateral force of 11.36 N at max lateral position of 2.5 mm by above chosen working conditions, which is enough to overcome the 2.4 kg weight so as to be able to levitate and stabilize the rotational shaft.

3. Running performances

Figure 6. Levitation force curves of lower SMB

Figure 7. Lateral force curves of lower SMB

Figure 8. Photo of the double axial SMBs system prototype in free rotation with a transformer
The final fabricated prototype is presented in figure 8. Before the running experiment, the upper and lower SMB were simultaneously field cooled at respective FCH, i.e. 3 mm and 15 mm, when the rotational shaft was vertically held at the centreline of the system by two circular clamps. This field cooling process would last about 15 minutes to make the YBCO bulks into superconducting state. After that, the positions of upper and lower SMBs needed to make some adjustments to guarantee the same WH of 5 mm. By taking off the clamps, the rotational shaft was observed to be levitated freely between the two SMB stators. If a force acted on the shaft along the circumferential direction, the shaft could rotate freely, and the rotation time could keep from few to dozens of minutes depending on the power of force. The free and stable rotation phenomenon has further verified the former conclusion that the double axial SMBs can levitate the 2.4 kg rotor shaft stably.

Based on the stable levitation, the spin-down experiments were conducted. A transformer was used to control the motor by changing the voltage of the power supply, as shown in figure 8. After the SMB system was accelerated to max rotational speed of 3000 rpm, the motor was shut down. Then the spin down phenomena of the SMB system was observed. During the gradual fall of the rotation speed, two obvious resonance rotational speeds were observed where the vibration of the rotor was sharply increased. Moreover, it was observed that the system at high speed was more stable than that of at low speed, besides the resonance speeds. To find out the resonance speeds of the system, the pulse response experiments were performed using a pulse analyzer of B&K Company with a tri-axial accelerometer. The experimental processes were identical with that in [18].

The pulse response experiments of the double SMBs system in axial and radial directions were both performed. Figure 9 and 10 showed the axial pulse response curves in time and frequency domain respectively. The pulse response curves in time domain is a damped free vibration curve, which seems to decrease exponentially, as shown in figure 9. While the curves in frequency domain curves (figure 10) has an obvious peak which can be considered as resonance frequency. So the resonance frequency in axial direction of the system is 20 Hz. The pulse response results in radial direction are similar to the above results. The difference is that the resonance frequency in radial direction takes place at 9.5 Hz. According to the two resonance frequencies, it was deduced that the resonance rotational speeds would take place at 570 rpm and 1200 rpm. So in order to get stable running performance, the rotational speed of the double SMBs system should avoid above resonance speeds.

4. Summary and Outlook
Based on the stable levitation and suspension properties of bulk HTSC in applied magnetic field, a double-axial-SMB system prototype has been fabricated. The upper and lower SMBs are respectively used to suspend and levitate the shaft. The levitation and lateral force experiments show that the SMB system is enough to levitate and stabilize the 2.4 kg shaft. Combined with an inductive motor, the
SMB system can be accelerated to 3000 rpm. During the spin-down experiments, two obvious resonance rotational speeds were observed where the vibration of the system sharply increased. The axial and radial pulse response experiments further show that the resonance phenomena will take place at 570 rpm and 1200 rpm. To get a stable running demonstration, it is suggested to avoid the two resonance speeds. At present, the SMB system can be used to demonstrate the flux-pinning property of bulk HTSC for stable levitation and suspension and the principle of SMB to visitor. Next, a DC PM brushless-motor with corresponding control circuit will be appended to realize an FESS prototype.

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