Position control of active magnetic levitation using sphere-shaped HTS bulk for inertial nuclear fusion

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Abstract. We have developed an active magnetic levitation system that comprises a field-cooled disk-shaped or sphere-shaped HTS bulk and multiple ring-shaped electromagnets. In this system, the levitation height of HTS bulk can be controlled by adjusting the operating current of each electromagnet individually. Further, the application of the vertical noncontact levitation system is expected due to its levitation stability without mechanical supports. We assume that this system is applied to inertial nuclear fusion. However, one of the important issues is to achieve position control with high accuracy of the fusion fuel in order to illuminate the target evenly over the entire surface. Therefore, this system is applied to the levitation and position control of a sphere-shaped superconducting capsule containing nuclear fusion fuel. In this study, we designed and constructed a position control system for the sphere-shaped HTS bulk with a diameter of 5 mm by using numerical simulation based on hybrid finite element and boundary element analysis. We then carried out the experiment of levitation height and position control characteristics of the HTS bulk in this system. With regard to position control, accuracies within 59 μm are obtained.

1. Introduction

High-temperature superconducting bulk (HTS bulk) materials are expected to be used for superconducting flywheels, magnetic levitation systems, superconducting permanent magnets, motors, and so on because of their improved critical current density and mechanical strength [1], [2]. An active magnetic levitation system containing electromagnets (hereinafter referred to as a 'coil') allows one to control the levitation height and force of HTS bulk, but not its levitation stability. With this background, we have been researching and developing HTS for electromagnetic applications [3]-[5]. In this study, we assume that an active levitation system is applied to inertial nuclear fusion. The principle of inertial nuclear fusion is as follows: a giant laser is applied around the surface of a pellet of a nuclear fusion fuel, causing implosion and nuclear fusion reaction. However, one of the important issues is to achieve high-accuracy position control of the fusion fuel, which consists of deuterium and tritium, in order to illuminate the target evenly over the entire surface. Therefore, active magnetic levitation is applied to the levitation and position control of a sphere-shaped superconducting capsule containing nuclear fusion fuel.

In this presentation, we designed and constructed a position control system for sphere-shaped HTS bulk with a diameter of 5 mm by using numerical simulation based on hybrid finite element and boundary element analysis [6]. Subsequently, we carried out an experiment to determine the levitation
height and position control characteristics of the sphere-shaped HTS bulk in the constructed levitation system. We also investigated the shielding current distribution within the HTS bulk during the levitation by using numerical simulation.

2. Experimental setup

We focused our attention on the spatial resolution of the levitation system, and accordingly decided the shape and distribution of the coils with a high degree of accuracy. The levitation height vs. current characteristics decides the spatial resolution and the control area determined by the position control system. We can control the levitation height with a high degree of accuracy as the levitation height change rate (levitation height change/current change) becomes low. Therefore, numerical simulation based on hybrid finite element and boundary element analysis is conducted in order to reduce the levitation height change rate to the least value. In this study, the experimental setup was based on the following five conditions. The design parameters are the inner diameter of the coils and the gap between the coils.

- Levitating the sphere-shaped HTS bulk with a diameter of 5 mm.
  (Critical current density: $J_c = 1 \times 10^8$ A/m$^2$.)
- The cross section of the coils was 20 mm in width and 15 mm in height.
- The number of coils was three.
- The upper limit of each coil current was 15 A.
- First position of the bottom of the HTS bulk is 2 mm upside of the Coil 1.

From the numerical simulation, we obtained the specifications of the system (Fig. 1, Table 1). A programmable logic controller (PLC) containing a CPU and a memory IC receives the input signal from the laser displacement meter, and sends out the output signal to the amplifier according to the previously programmed conditions.

![Figure 1. Schematic representation of the experimental setup.](image)

(a) Measurement of levitation characteristics.
(b) Position control system.
Table 1. Specification of HTS bulk and coils.

| HTS bulk | Coil 1 | Coil 2 | Coil 3 |
|----------|--------|--------|--------|
| Shape    | Sphere |        |        |
| Material | DyBCO  |        |        |
| Diameter | 5 mm   |        |        |
| Weight   | $4 \times 10^{-4}$ kg |        |        |
| Inner diameter | 27 mm | 18 mm | 8 mm |
| Outer diameter | 67 mm | 56 mm | 48 mm |
| Thickness | 16 mm | 17 mm | 18 mm |
| Turns of coil | 250 | 250 | 250 |

3. Principle of levitation and stabilizing HTS bulk in the horizontal direction

3.1. Principle of levitating HTS bulk

When HTS bulk is placed in an external magnetic field, shield current appears on its surface. The external magnetic field and shield current cause Lorentz force. The HTS bulk is levitated due to the Lorentz force caused by the external field in a radial direction and the shield current (Fig. 2).

3.2. Stabilizing HTS bulk in the horizontal direction

The Lorentz force caused by the external field in the vertical direction and shield current produces a horizontal force on the HTS bulk. In ideal magnetic fields produced by coils, the HTS bulk can remain on the centre axis (z-axis) of the coils. However if the HTS bulk moves away from the centre, it is ejected from the magnetic field (Fig. 3(a)). Therefore, we energize the current to Coil 3 with Coil 1 and Coil 2 of the opposite direction to produce the magnetic field distribution as shown in Fig. 3(b). This causes the HTS bulk to return to the centre of the coils automatically in case it moves away from the centre. Fig.4 shows the magnetic field distributions along the horizontal direction of the experimental setup shown in Fig. 1.

Figure 2. Principle of levitating HTS bulk.

Figure 3. Principle of stability of horizontal direction.
4. Levitation height property
The levitation height decides the control area of the system, while the levitation height change rate controls the target height. When this system will be installed to the inertial nuclear fusion, the control system will have high accuracy if the levitation of the HTS bulk is not controlled until it reaches the control area, after which dynamic fine control will be applied to the HTS bulk using the control coil at the control area. Therefore, we selected Coil 1 for field-cooling, Coil 2 for levitation and control and Coil 3 for stabilizing HTS bulk in the horizontal direction.

4.1. Experimental procedure
1) The DyBCO bulk is placed at an initial position shown in Fig.1 (a). After the lowermost coil, Coil 1, is energized up to 5 A, the bulk becomes superconducting by filling the container with liquid nitrogen.
2) The coil current is gradually reduced to zero. Some magnetic field, called ‘trapped field’, remains inside the bulk. The trapped magnetic field is directed upward.
3) The topmost coil, Coil 3, is energized up to 15 A opposite to Coil 1 and the second coil, Coil 2.
4) Coil 1 is energized up to 15 A again.
5) After the current in Coil 1 is set to 15 A, Coil 2 is energized up to 15 A.
6) A laser displacement meter measures the levitation height, the position of the bulk.

4.2. Results and discussion
One of the experimental and numerical results of the levitation height are shown in Fig. 5 by plots and a solid line, respectively. As shown in Fig.5, the result of the numerical simulation is in excellent agreement with the experimental result.
agreement with the experimental result. In addition, as a result of several experiments, repeatability in the result can be observed. Therefore, the validity of the developed computer program was confirmed. We believe that the control performance is enhanced if the current change rate in the vicinity of the target levitation height reduces. From the result, the DyBCO bulk starts to levitate after operating the second coil. We control the operating current in the second coil for achieve position control of the DyBCO bulk. Moreover, it can be seen in Fig. 5 that the maximum levitation height is approximately 18-21 mm. In other words, the control region of this position control system ranges from 18 mm to approximately 21 mm.

5. Position control

5.1. Experimental procedure
The experimental setup for position control is almost identical to that for the levitation height property. The difference is that the second coil is connected to a programmable logic controller instead of a DC power source. The experiment proceeded through the following steps:
1) The DyBCO bulk is placed at the initial position shown in Fig.1 (b). After the lowermost coil, Coil 1, is energized up to 5 A, the bulk becomes superconducting by filling the container with liquid nitrogen.
2) The coil current is gradually reduced to zero. Some magnetic field, called ‘trapped field’, remains inside the bulk. The trapped magnetic field is directed upward.
3) The top coil, Coil 3, is energized up to 15 A opposite to Coil 1 and the second coil, Coil 2.
4) Coil 1 is energized up to 15 A again.
5) After the vicinity of the target levitation height is set, the programmable logic controller is operated according to the feedback control.
6) The laser displacement meter measures the levitation height (scan time 200 ms).
5.2. Results and discussion

The target levitation height is set to 18 mm, and the experiments are operated several times. Fig. 6 shows the result of position control, and Fig. 7 shows the error of position control between the target levitation height and the observed height. (The resolution is approximately 2 μm.) The standard variation of the observed height from when the HTS bulk begins to be controlled is assumed to be 58.58 μm or less. In order to apply this system to inertial nuclear fusion, the standard variation must be 10 μm or less. This difference is mainly attributed to the bubbles of liquid nitrogen generated by copper coil excitation. From the above results, we can conclude that a position control system with very high accuracy has been achieved.

6. Summary

A noncontact position control system for magnetic levitation in the vertical direction based on feedback control theory using a sphere-shaped HTS bulk with a diameter of 5 mm has been fabricated and tested. The target levitation height was maintained with high accuracy. As a future study, we must control the HTS bulk with a diameter of 1-2 mm supposing that it is used in inertial nuclear fusion.

7. References

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