Position Control of Active Magnetic Levitation using YBCO Bulk and Multiple Electromagnets

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Abstract. We have been developing an active magnetic levitation system composed of field-cooled disk-shaped YBCO bulk and multiple ring-shaped electromagnets which are vertically piled up. We have demonstrated and reported that the levitation height, as well as stability, can be remarkably improved by adjusting the operating current of each electromagnet individually. In this study, we constructed a noncontact position control system in the vertical direction based on the feedback control theory and the electromagnetic field analyses considering superconducting characteristics of the YBCO bulk. Depending on levitation height, the operating current in the electromagnets is controlled automatically. The system consists of two ring-shaped copper-winding electromagnets without iron core and a ring-shaped YBCO bulk magnetized by the field-cooling process. We carried out experiments to verify the feasibility of noncontact position control system. In the experiment for position control, the levitation height maintained a target position accurately, and responded smoothly to changing target position. In addition, we aimed at the construction of the position control system with higher accuracy using the numerical simulation based on the finite element method analyses. And, the position control system that piled up three electromagnets was designed and constructed. Concretely, accuracies of the position control within $28\mu\text{m}$ were obtained. Final goal of our study is to apply the levitation system to the inertial nuclear fusion in which the accuracy as high as several $\mu\text{m}$ would be required.

1. Introduction

In active levitation using electromagnets (hereinafter referred to as “coil”) and bulk superconductors, the levitation height and force can be controlled by the current of coils; moreover, uncontrolled stable levitation is achievable, which arouses great expectations for vertical magnetic levitation transport systems. Although the levitation height may be enhanced by using a large coil or superconducting magnet, neither system is effective from the point of view of energy efficiency because of increasing leakage flux with levitation height. We have fabricated and tested a new type of active magnetic levitation system composed of five flat solenoid coils piled up on the vertical axis with a certain gap. “Continuous levitation” in the vertical direction has been successfully achieved by controlling the current of each coil individually [1]. We have also numerically investigated the electromagnetic phenomenon within the bulk superconductor using a developed computer program based on the finite element method (FEM) to clarify the mechanism of the continuous levitation [2]. In this paper, we focus attention on “position control”, and describe a newly constructed noncontact position control system in the vertical direction.
based on the feedback control theory, using field-cooled ring-shaped YBCO bulk and three solenoid coils piled up on the vertical axis with a certain gap. Final goal of our study is to apply the levitation system to the inertial nuclear fusion in which the accuracy as high as several μm would be required.

2. Levitation height property

2.1 Experimental setup

The experimental setup for measurement of levitation height is schematically drawn in Fig. 1. A ring-shaped YBCO bulk, which was processed by the QMG method, was used and three ring-shaped copper-winding coils were piled up on the vertical axis with an optimized gap of coil1-2 8 mm, coil 2-3 32mm. The specifications of ring-shaped YBCO bulk and coils are listed in Table 1. The YBCO bulk is magnetized by field cooling using the undermost coil shown in Fig.1. The bulk is exposed to an external magnetic field of 0.03 T at a coil current of 10A. The YBCO bulk and the coils are placed in a styrofoam container filled with liquid nitrogen boiling at 77 K. As shown in Fig.1, the levitation height was measured by using a laser displacement meter.

The experiments proceed through the following steps:

Step 1) The YBCO bulk is placed at an initial position as shown in Fig.1. After the undermost coil is energized up to 10 A, the bulk is transited to the superconducting state by filling the container with liquid nitrogen.

Step 2) The coil current is gradually reduced to zero. Some magnetic field, called “trapped field”, remains inside the bulk. The direction of the trapped magnetic field is upward.

Step 3) The undermost coil is energized up to 15 A again.

Step 4) After the current of the undermost coil is set to 15 A, the second coil is energized up to 15 A.

Step 5) After the current of the undermost and second coil is set to 15 A, the third coil is energized up to 15 A.

Step 6) The levitation height, that is the position of the bulk, is measured by a laser displacement meter.

Table 1. Specification of RING-SHAPED YBCO bulk superconductor and coils.

| bulk          |          | coil          |          |
|---------------|----------|---------------|----------|
| Inner Diameter (mm) | 23       | Inner Diameter (mm) | 58       |
| Outer Diameter (mm)  | 46       | Outer Diameter (mm)  | 110      |
| Thickness (mm)       | 15.5     | Thickness (mm)       | 12       |
| Mass (g)             | 125      | Number of turns    | 250      |
| Critical current density | 7×10⁶ |
2.2 Results and discussion

The experimental and simulation results of levitation height property are shown in Fig. 2 by plots and solid line, respectively. As seen in Fig. 2, the simulation is excellent agreement with experimental result. Therefore the validity of the developed computer program was confirmed.

We thought that the performance of the control went up if the current change rate in the vicinity of the target levitation height became small. From the result, the YBCO bulk starts to levitate after operating the third coil. We controlled the operating current of the third coil for the position control of the YBCO bulk. Moreover, it can be seen in Fig. 2 that the maximum levitation height is about 30-32 mm. That is, the control region of this position control system is 30mm to about 32 mm.

3. Position control
3.1 Experimental setup

The experimental setup for position control is almost the same as that for levitation height property. A different point is that the third coil is connected to a programmable logic controller instead of DC power source.

The programmable logic controller that contained CPU and memory IC, can receive the input signal from the laser displacement meter, and send out the output signal to the amplifier according to the conditions programmed in advance.

The experiments proceed through the following steps:
Step1-4) The same procedure as the experiment of levitation height property.
Step5) After the vicinity of the target levitation height is set, the programmable logic controller is started to operate according to the feedback control.
Step6) The levitation height is measured by the laser displacement meter. (scantime 100ms)
3.2 Results and discussion

The target levitation height is set to 30mm and 31mm, and we carried out the experiments several times. Figures 4 and 5 show the results of the position control and the average of difference between the target levitation height and the observed levitation height. (Resolution is about 2\(\mu\)m.) The average of the difference between the target levitation height and the observed height was able to be suppressed to 20\(\mu\)m or less. This difference is due mainly to the bubbles of liquid nitrogen generated by the copper coil excitation. From the above results, the position control system with very high accuracy was achieved.

![Figure 4. Results of position control](image)

![Figure 5. The difference between the target levitation height and the observed levitation height](image)

4. Conclusion

The noncontact position control system in the vertical direction for the magnetic levitation based on the feedback control theory was fabricated and tested. The levitation height maintained the target levitation height with high accuracy. The position control system with very high accuracy was achieved. As the future study, experiments and numerical simulations on electromagnetic phenomenon when using a sphere-shaped YBCO bulk is carrying out as a preliminary investigation.

References

[1] Ueda H, Hayashi H, Ishiyama A and Tsuda M 2002 Physica C 372-376 1466-1469
[2] Kamoshida R, Ueda H and Ishiyama A 2003 IEEE Trans. on Appl. Supercond. 13 2157-2160