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# Characteristics of active-maglev system using YBCO bulk and multiple electromagnets

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## Abstract

One useful feature of the active-maglev system is that levitation height is adjustable by varying operating current in electromagnets. To improve the levitation height, we have designed and constructed a new type of active-maglev system with two electromagnets instead of using a larger single electromagnet. The levitation height, as well as stability, was remarkably improved by adjusting the operating current of each electromagnet individually. Although the bulk is levitated up to high position, the lower electromagnet is continued to operate in continuous levitation using multiple electromagnets. It is waste that the lower electromagnet is continued to operate. The required energy for the electromagnet operation should be minimized. In this paper, we tried to realize continuous levitation with keeping the total operating current constant in five-electromagnet active-maglev system and investigate electromagnetic behavior within the bulk using a newly developed FEM computer program. Continuous levitation was successfully achieved under the desired operating condition. Agreements between experiment and analysis were excellent.

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## 1. Introduction

The useful features of active-maglev system, comprised of high-temperature superconducting bulk and electromagnet, are (1) that levitation height and levitation force are adjustable by changing the operating current in electromagnet; (2) stable levitation can be also achieved without any control systems. Maximum stable levitation height, however, is restricted by the stability of

bulk and the magnetic field distribution generated by the electromagnet. Although the levitation height may be improved by using a large electromagnet or a superconducting magnet, neither system is effective from the point of view of the energy efficiency because of increasing leakage flux with levitation height. Therefore, we have designed and constructed a new type of active-maglev system using YBCO bulk and multiple electromagnets. Using this system, we realized ‘continuous levitation’ in the vertical direction and enhanced the levitation height [1].

Considering a real application to maglev transporter in the vertical direction, we must realize continuous levitation using the larger number of

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electromagnets and enable the levitation height to control freely in the vertical direction by adjusting the operating current of each coil individually and investigate electromagnetic behavior within the bulk using a newly developed FEM computer program.

## 2. Experimental

Experimental setup for the measurements of levitation height is schematically drawn in Fig. 1. We prepared a disk-shaped YBCO bulk with 46 mm in diameter, 13 mm thickness and 148 g weight. Five electromagnets (hereinafter referred to as “coils”) wound with copper wire were used in the experiment. The inner and outer diameters of all coils are 60 and 116 mm, respectively. The number of turns and the coil height of all coils are 250 and 12 mm, respectively. These coils were piled up in the vertical direction with the constant air gap of 4 mm. We can adjust the operating current of each coil individually.

Although the bulk is levitated up to high position, the lower electromagnet is continued to operate in continuous levitation using multiple coils. It is waste that the lower electromagnet is continued to operate. The required energy for the coil

operation should be minimized. We tried to realize continuous levitation with keeping the total operating current constant in five-coil system according to the following steps:

- (1) Place the normal-state bulk at the center of top surface of coil 1 and let it transit to the superconducting state in the presence of DC magnetic field generated by coil 1. The field-cooling current is 10 A. The bulk, located on the top surface of coil 1, is exposed to the magnetic field of 0.08 T at the current in coil 1 of 10 A.
- (2) Reduce the DC magnetic field to zero and trap the magnetic flux.
- (3) Control the current of five coils with keeping the total current constant as shown in Fig. 2(b).

A typical experimental result of continuous levitation using five coils is shown in Fig. 2(c). As shown in Fig. 2(c), continuous levitation was successfully achieved with keeping the total operating current constant in five-coil system.

## 3. Numerical simulation

We evaluated the electromagnetic behavior within the bulk and the characteristics of levitation height using a newly developed simulation program based on the finite element method [1–4].

Although the governing equation for supercurrent in high- $T_c$  superconductors is almost the same as ones for eddy currents in normal conductors, the relationship of supercurrent density,  $J_{SC}$ , and the electric fields,  $E$ , is nonlinear. We adopt the critical state model. On an assumption that Ohm’s law equivalently comes into existence in the superconductor, we modify the conductivity of superconductor,  $\sigma_{SC}$ , to make  $|J_{SC}|$  not higher than the critical current density,  $J_C$  by using the following iterative method [2,3].

- (1) Initial value of  $\sigma_{SC}$  is assumed sufficiently large in all elements.
- (2) If  $|J_{SC}| > J_C$  then

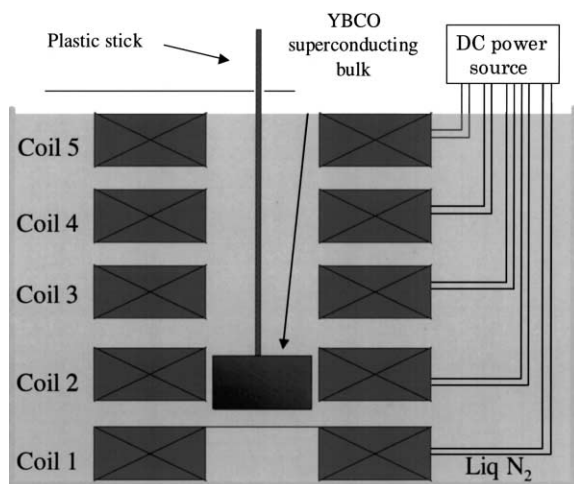


Fig. 1. Schematic drawing of an experimental setup for levitation height measurement.

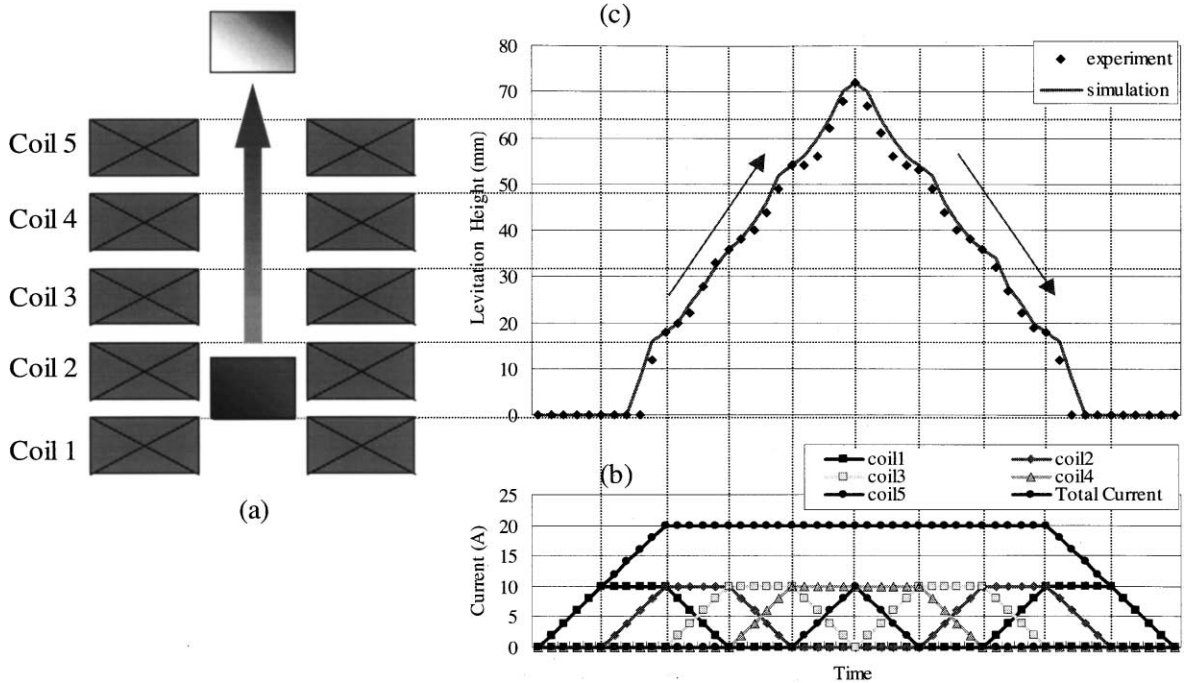


Fig. 2. Results on levitation height in five-coil system with keeping total coil current constant: (a) concept of continuous levitation, (b) operating current, (c) levitation height.

$$\sigma_{SC-NEW} = \frac{J_C}{|J_{SC}|} \sigma_{SC-OLD} \quad (1)$$

and solve the governing equation to get a new distribution of  $J_{SC}$ . Step (2) is repeated until  $|J_{SC}|$  does not exceed  $J_C$  in all elements of superconductor.

The levitation force can be evaluated as Lorentz force and the levitation height is calculated in the algorithm as shown in Fig. 3.

The equivalent critical current density of the bulk was assumed to be  $1.0 \times 10^8 \text{ A/m}^2$  in the analysis. The numerical results in five-coil system are shown in Fig. 2. Agreements between experiment and analysis are excellent. Supercurrent distribution within the bulk is investigated in increasing and decreasing processes of the operating current. The bulk is moved to balance the levitation force with the weight of the bulk because of changing the supercurrent distribution against varying external magnetic field.

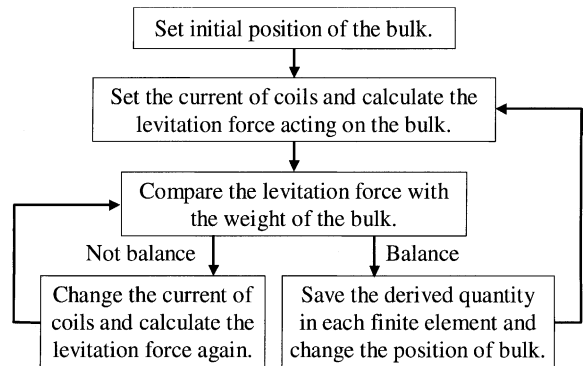


Fig. 3. Algorithm for levitation height calculation.

The external magnetic field changes slowly in this experiment. Therefore, the computer program, considering the critical state model, successfully simulated the electromagnetic behavior and the levitation characteristic. It cannot, however, represent the dynamic electromagnetic phenomena within the bulk. We must consider the  $E$ - $J$  char-

acteristic of the bulk to simulate the behavior within the bulk in time-varying magnetic field [4].

#### **4. Summary**

Although the bulk is levitated up to high position, the lower electromagnet is continued to operate in continuous levitation using multiple coils. It is waste that the lower coil is continued to operate. The required energy for the coil operation should be minimized. Therefore, We tried to realize continuous levitation with keeping the total operating current constant in five-coil system. Continuous levitation was successfully achieved

under the desired operating condition. These results imply that we can realize continuous levitation using the large number of coils and control the bulk movement freely in the vertical direction by adjusting the operating current of each coil individually.

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