A New Type of Active-Maglev System Using YBCO Bulk and Multiple Electromagnets

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A New Type of Active-Maglev System Using YBCO Bulk and Multiple Electromagnets

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***Abstract*—We present a new type of active-maglev system consisting of a disk-shaped superconducting bulk (YBCO) and multiple electromagnets. Using the active-maglev system composed of five electromagnets, we demonstrated continuous levitation and verified that the levitation height, as well as stability, could be remarkably improved by adjusting operating current of electromagnet individually. Electromagnetic behavior within the bulk was investigated numerically by the finite element method (FEM) adopting the Bean model. Agreements of levitation force and height between experiment and analysis were good. Suitable electromagnet operation for continuous levitation in terms of consumed operating energy was also investigated. It was found in analysis that continuous levitation could be realized efficiently by adopting a three-electromagnet operation and the operating procedure is applicable to multiple-electromagnet system. Therefore, based on the assumption of constant total operating current of three electromagnets, we numerically investigated the relationship between the operating procedure and levitation force in a five-electromagnet system as a function of levitation height. Maximum allowable weight of float (superconducting bulk and load) was evaluated through the estimation of minimum levitation force during continuous levitation as a function of air gap between electromagnets.**

***Index Terms*—Electromagnet, FEM, magnetic levitation, superconduting bulk.**

I. INTRODUCTION

ONE OF the useful features of active-maglev system, comprised of high-temperature superconducting bulk and electromagnet, is that levitation height is adjustable by changing the operating current in electromagnet. Maximum stable levitation height, however, is restricted by bulk stability and 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 constructed and tested a new type of active-maglev system composed of two electromagnets piled up on the vertical axis with a certain air gap [1]. "Continuous levitation" in the vertical direction was successfully achieved in the coil system. We have numerically investigated the electromagnetic phenomenon within superconducting bulk using a newly developed FEM code to clarify the mechanism of the continuous levitation.

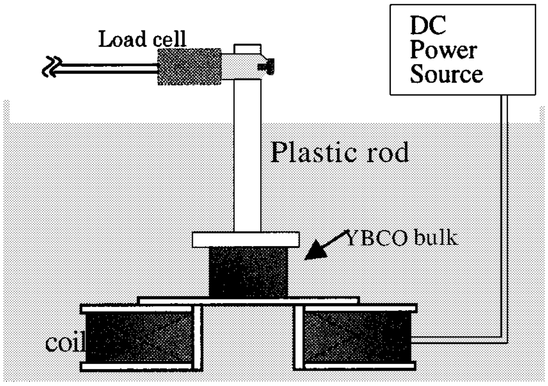

Fig. 1. Experimental setup for measurement of levitation force.

For the application of the continuous levitation to real maglev system such as "axial transporter," maximum allowable weight of float and consumed energy during continuous levitation are key parameters in the system. Therefore, using our developed simulation code, we investigated suitable combination of operating coil currents giving the largest levitation force. The most suitable air gap between electromagnets was also discussed.

II. EXPERIMENTS

We carried out two experiments: 1) measurement of levitation force using an electromagnet for the numerical evaluation of equivalent critical current density within bulk; and 2) realizing continuous levitation using five electromagnets (hereinafter electromagnet is referred to as "coils").

We prepared a disk-shaped YBCO bulk with 47 mm in diameter and 16 mm thickness. Five coils wound with copper wire were used in experiment. The inner and outer diameters of both coils are 58 mm and 118 mm, respectively.

The number of turns and the coils height are 251 and 13 mm, respectively. Note that the bulk, located on the top surface of coil, is exposed to the magnetic field of 0.08 T at the operating current of 10 A. Experimental setup for the measurements of levitation force is schematically drawn in Fig. 1.

To evaluate equivalent critical current density within bulk, levitation force were measured by a loadcell according to the following steps.

1) Place a normal-state bulk at the center of top surface of coil and let it become superconducting state in the presence of DC magnetic field generated by the coil.
2) Reduce the DC magnetic field to zero.

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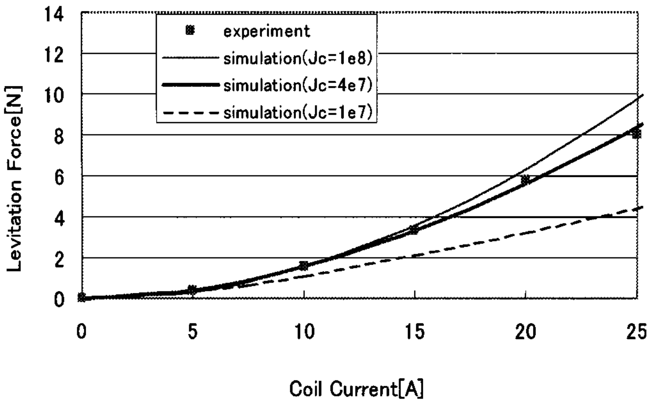

Fig. 2. Results on levitation force with no trapped field.

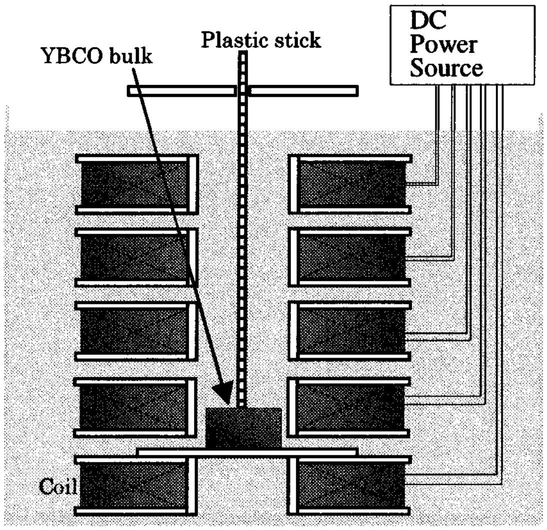

Fig. 3. Schematic drawing of an experimental setup for levitation height measurement.

3) Measure the levitation force by the loadcell, as a function of coil current.

An experimental result of levitation force is shown in Fig. 2. The levitation force gradually increases with operating coil current.

Fig. 3 shows schematically drawing of an experimental setup of five-coil system for continuous levitation and the measurement of levitation height. The specifications of coil and bulk are the same with those in Fig. 1. In continuous levitation using multiple coils, the required energy for the electromagnet operation should be minimized.

Therefore, we tried to realize continuous levitation in the five-coil system by keeping total operating current of three coils constant. The air gap between coils was 4 mm. The operating procedure was as follows.

1) Place a normal-state bulk at the center of top surface of the lowest coil, defined as coil1, and let it become the superconducting state in the presence of DC magnetic field generated by coil1. The field-cooling current is 10 A.
2) Reduce the DC magnetic field to zero and trap the magnetic flux.
3) Operate the coil current individually with keeping the total operating current constant.

An experimental result of continuous levitation of five-coil system is shown in Fig. 4(c). As shown in Fig. 4(c), continuous levitation was successfully achieved with keeping the total operating current constant in the five-coil system.

III. ANALYSIS

We have developed some simulation codes to investigate electromagnetic characteristics of HTS bulk system [1]–[4]. We newly developed a simulation code based on the finite element method to evaluate levitation force and height in continuous levitation. The simulation technique generally used in eddy current problem of normal metal was used in this simulation. The critical state model and a nonlinear relationship between supercurrent density, $\boldsymbol{J}_{\mathrm{SC}}$, and the electric fields, $\boldsymbol{E}$, was adopted. To satisfy the Ohm's law and the critical state model within superconductor, equivalent conductivity of superconductor, σ_{SC}, was adjusted by the following iterative method.

1) Initial value of σ_{SC} is assumed sufficiently large.
2) If $|\boldsymbol{J}_{\mathrm{SC}}| > J_{\mathrm{C}}$, then

$$\sigma_{\mathrm{SC\text{-}new}} = \frac{J_{\mathrm{C}}}{|J_{\mathrm{SC}}|}\sigma_{\mathrm{SC\text{-}old}} \tag{2}$$

and solve the governing equation to get a new distribution of $\boldsymbol{J}_{\mathrm{SC}}$.

Step 2) is repeated until $|\boldsymbol{J}_{\mathrm{SC}}|$ does not exceed the critical current density, J_{C}, in all elements of the superconductor. The levitation force can be evaluated as Lorentz force and the levitation height is obtained by balancing the levitation force with gravity of bulk.

The computed results of levitation force as a function of critical current density are shown in Fig. 2. From the results, equivalent critical current density of 4.0×10^7 A/m^2 was assumed in the following analysis. The computed levitation height in continuous levitation of five-coil system is shown in Fig. 4. Agreement between experiment and analysis is excellent. Supercurrent distribution within the bulk was investigated in both increasing and decreasing processes of the operating current. Although the supercurrent distribution is changed with external magnetic field, the distributions at the same levitation height became the same; supercurrent distribution in increasing process of operating coil current agrees with that of decreasing process. This result implies that the levitation height is controllable and the repeated operation of continuous levitation can be achieved in multiple-coil system.

IV. DISCUSSION

It was observed in experiment that continuous levitation could be realized by the coil operation that operating currents of all lower coils than bulk are maintained or increased. In continuous levitation in multiple-coil system, however, the required energy for coil operation should be minimized. Therefore, we applied an operating current limitation for more efficient levitation; the total operating current of arbitrary three coils assumed to be constant.

As shown in Fig. 4, continuous levitation was achieved successfully in this operating method. The experimental and nu-

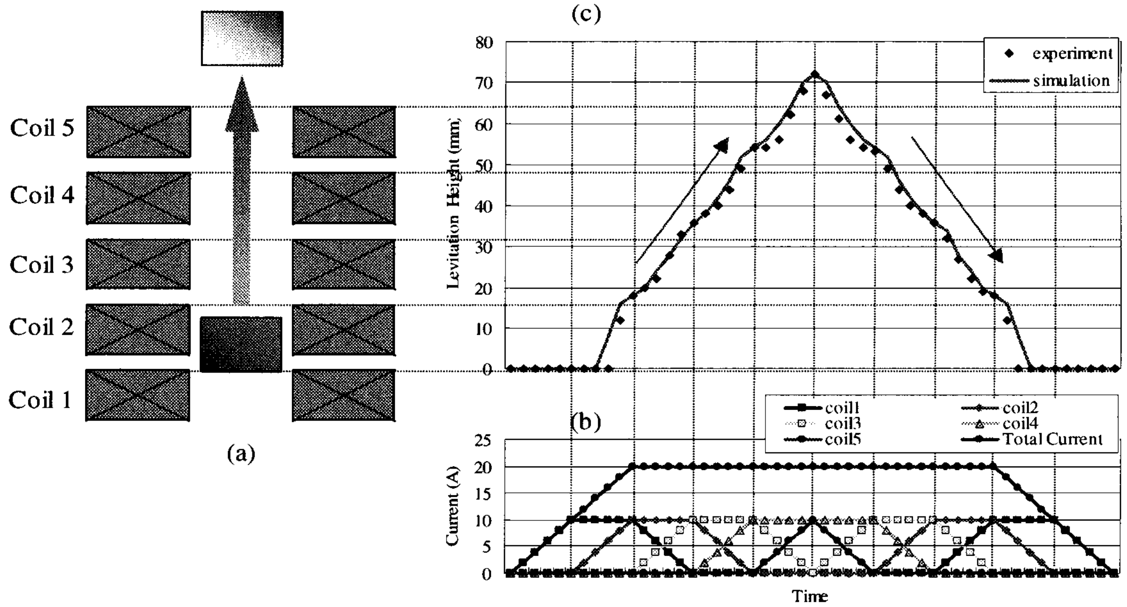

Fig. 4. Results on levitation height in five-electromagnet system with keeping total coil current constant. (a) Concept of continuous levitation, (b) operating current, (c) levitation height.

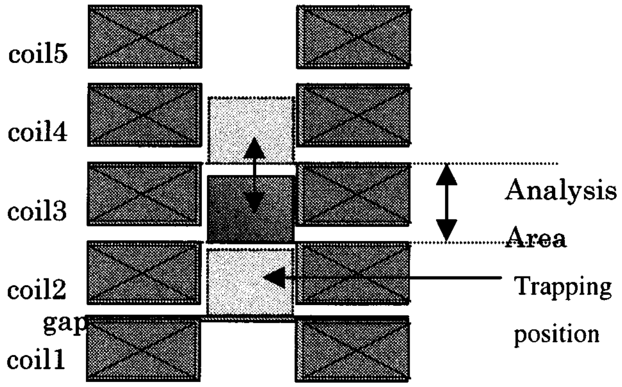

Fig. 5. Analysis setup for calculating the maximum levitation force.

merical results imply that this operating method can be applied to multiple-coil system regardless of number of coils. Based on the results, we numerically investigated the characteristics of continuous levitation, especially suitable combination of operating current and maximum allowable weight (load).

In suitable combination of operating current in five-coil system, the following two conditions were considered in analysis: 1) current limitation in each coil; and 2) constant total operating current in arbitrary three coils. We assumed the field-cooling current of 10 A, the total operating current of 30 A and the current limitation of 15 A.

Maximum levitation force within a simulation region, shown in Fig. 5, was evaluated repeatedly as functions of operating current of three coils. This means that the combination of operating current generating maximum levitation force, $F_{\mathrm{MAX\text{-}LOCAL}}$, depends on the bulk location. One of the numerical results of $F_{\mathrm{MAX\text{-}LOCAL}}$ at the lowest position in the simulation region, defined as $z = 0$ mm, is shown in Fig. 6. It was assumed that field-cooling process was performed by coil1. In Fig. 6, coil1, coil2 and coil3 represent the first, second and third coils counted from the lowest coil in Fig. 5, respectively. The operating current of coil2 was constant (12 A) and those of coil1 and coil3 were changed linearly. Fig. 6 shows $F_{\mathrm{MAX\text{-}LOCAL}}$ at $z = 0$ mm is 4.9 N at the operating current of 12 A, 15 A and 3 A in coil1, coil2 and coil3, respectively.

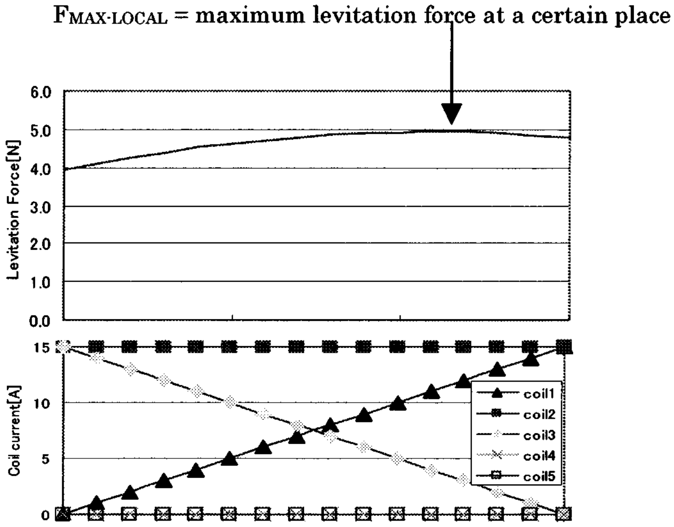

Fig. 6. Numerical results of levitation force.

Fig. 7 shows a numerical result of $F_{\mathrm{MAX\text{-}LOCAL}}$ as a function of the bulk location. It was found that the maximum levitation force, $F_{\mathrm{MAX\text{-}LOCAL}}$, depends on the bulk location, i.e., levitation height. In Fig. 7, the bulk-location giving minimum $F_{\mathrm{MAX\text{-}LOCAL}}$ was investigated numerically in the coil system. The minimum $F_{\mathrm{MAX\text{-}LOCAL}}$ defined as $F_{\mathrm{MIN\text{-}GLOBAL}}$, means the maximum allowable weight of float. Therefore, this is one of very important parameter in the design of real maglev system. Since the maximum allowable weight strongly depends on air gap between coils, we investigated the relationship between the maximum allowable weight and the air gap. A computed result

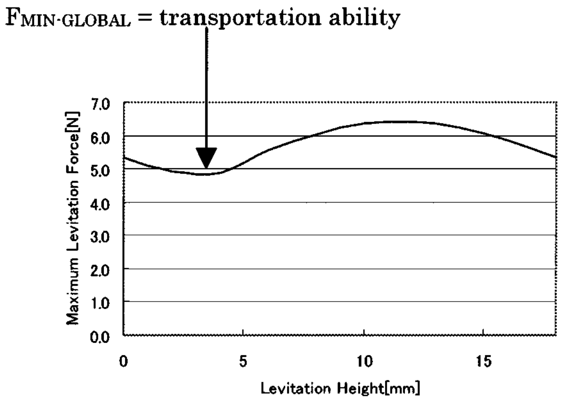

Fig. 7. Numerical results of maximum levitation force.

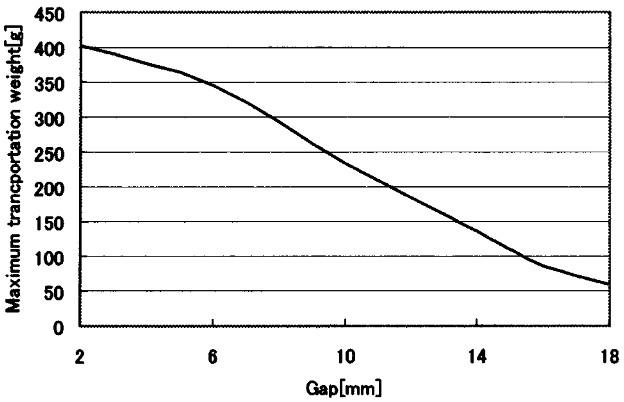

Fig. 8. Numerical results of transportation ability.

of the maximum allowable weight is shown in Fig. 8. As seen in Fig. 8, the smaller air gap, the larger allowable weight. This may be caused by the relationship between air gap and leakage flux.

Although small air gap is desirable in terms of maximum allowable weight, the number of required coils decreases with the air gap. The most suitable air gap and coil operation can be evaluated by this analysis.

V. CONCLUSIONS

In continuous levitation of multiple-coil system, the required energy for the coil operation should be minimized. We tried to realize continuous levitation in five-coil system with keeping the total operating current of three coils constant. Continuous levitation was successfully achieved in this operating method. The experimental and numerical results of levitation height in the five-coil system imply that continuous levitation can be achieved also in a larger number of coils and control levitation height freely. Maximum allowable weight of float was evaluated by calculating maximum levitation force as a function of levitation height. The most suitable air gap between coils is closely related to the maximum allowable weight and can be evaluated by FEM analysis of levitation force.

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