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A new type of active-maglev system using YBCO bulk and multiple electromagnets

H. Ueda [a], H. Hayashi [a], A. Ishiyama [a,*], M. Tsuda [b]

[a] *Waseda University, Ohkubo 3-4-1, Shinjuku-ku, Tokyo 169-8555, Japan*
[b] *Yamaguchi University, Tokiwadai 2-16-1, Ube, Yamaguchi 755-8611, Japan*

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Abstract

We present a new type of active-maglev system consisting of high-temperature superconducting bulk and multiple electromagnets. A prototype of the new active-maglev system composed of two solenoid type electromagnets located on the same axis was designed. Each electromagnet was operated individually; only the lower electromagnet had been operated until the bulk reached a certain level and then the upper electromagnet was started to operate with a constant current of the lower electromagnet. Lift and levitation height were investigated experimentally as functions of (1) the magnitude of trapped field; (2) the gap between the lower and upper electromagnets; and (3) the levitation height at which the upper electromagnet is started to operate. Independent of these parameters, 'continuous levitation' in the axial direction was achieved in the new active-maglev system. Electromagnetic behavior within the bulk was also investigated numerically by the finite element method, i.e. axial symmetry field analysis, using the magnetic vector potential. The experimental and computed results imply that levitation height can be remarkably improved by the continuous levitation using multiple electromagnets. © 2001 Published by Elsevier Science B.V.

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1. 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 the stability of bulk and the magnetic field distribution generated by the electromagnet [1,2]. 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 designed a new type of active-maglev system composed of two electromagnets located on the same axis with a certain air gap. Using this system, we realized 'continuous levitation' in the axial direction and enhanced the levitation height. Electromagnetic behavior within the bulk is also very important to clarify the mechanism of 'continuous levitation'.

* Corresponding author. Tel.: +81-3-5286-3376; fax: +81-3-3208-9337.
E-mail address: atsushi@mn.waseda.ac.jp (A. Ishiyama).

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2. Experiment

We prepared a disk-shaped YBCO bulk with 45.2 mm in diameter and 3.1 mm thickness. Experimental setup for the measurements of levitation height is schematically drawn in Fig. 1. Two electromagnets wound with copper wire were used in the experiment. The inner and outer diameters of both electromagnets are 57 and 117 mm, respectively. The number of turns and the magnet height are 251 and 13 mm in the upper magnet and 496 and 22.3 mm in the lower magnet, respectively. Note that the bulk, located on the top surface of the lower electromagnet, is exposed to the magnetic field of 0.08 T at the operating current in the lower magnet of 10 A. The levitation height were measured according to the following steps: (1) place the normal-state bulk at the center of top surface of the lower electromagnet and let it become the superconducting state in the presence of DC magnetic field generated by the lower magnet; (2) reduce the DC magnetic field to zero; and (3) measure and the levitation height by ruler, as a function of the magnet current.

3. Analysis

We have developed some simulation codes to investigate the electromagnetic behaviors in the various applications of HTS bulk [2,3]. We evaluated the electromagnetic behavior within the bulk and the characteristics of levitation height using a simulation code based on the finite element method. In this analysis, we adopted the critical state model and the magnetic vector potential method. The equivalent critical current density of the bulk was assumed to be 2.5×10^8 A/m^2 in the analysis.

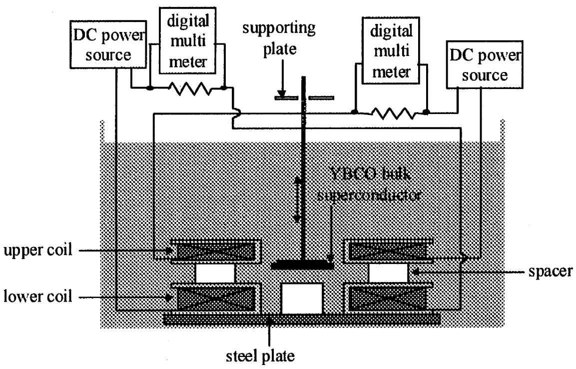

Fig. 1. Experimental setup for measurements of levitation height.

4. Results and discussion

4.1. Multiple-magnet system

We could not obtain large levitation height in single-magnet system because levitation height is restricted by magnetic field distribution and stability. Therefore, we designed a new type of active-maglev system comprised of two electromagnets and investigated the characteristics of lift and levitation height. Fig. 2 shows the basic concept of continuous levitation in the two-magnet system. It would be possible to realize the continuous levitation if the bulk could reach above the upper magnet by only the lower-magnet operation. We tried to perform the continuous levitation at the gap between the two magnets of 5 and 10 mm. Note that the field-cooling current was 5 A and the upper magnet was started to operate at the levitation height of 20 mm (5 mm gap) and 25 mm (10 mm gap). The relationships between the operating current and the levitation height at the gaps of 5 and 10 mm are presented in Fig. 3. The continuous levitation was successfully achieved in both cases. Agreement between experiment and analysis is very good. The maximum levitation height was 30 mm in the single-magnet system, while remarkable improved maximum levitation height of 75 mm in

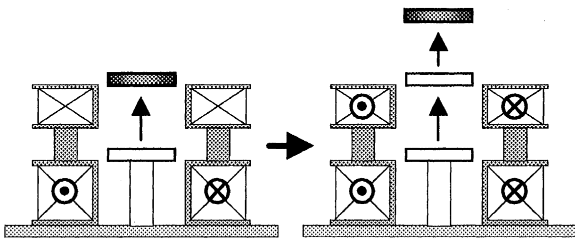

Fig. 2. Basic concept of continuous levitation.

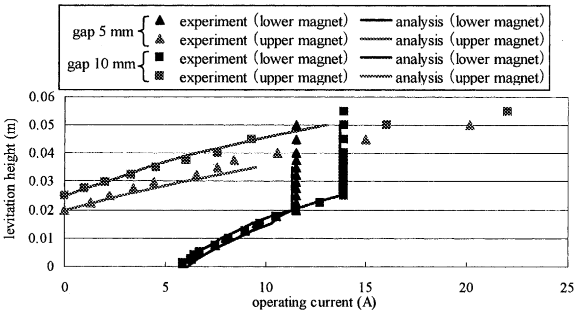

Fig. 3. Levitation height vs. operating current.

the two-magnet system; this implies that the further levitation height can be obtained using a larger number of magnets.

In this levitation method, however, the supporting plate, shown in Fig. 1, is indispensable to achieve the continuous levitation; this means that continuous 'stable' levitation cannot be realized without the supporting plate in this levitation method. In the single-magent system, the maximum stable levitation height without the supporting plate was 5 mm, so that the magnet height should be less than 5 mm in the levitation method of Fig. 2. In regard to energy efficiency, this levitation method is not desirable because many magnets are required to obtain large levitation height. Therefore, we tried to improve the stability and the efficiency using another levitation method, as shown in Fig. 4. The difference of the levitation methods between Figs. 2 and 4 is the levitation height at which the upper magnet starts to be operated. The continuous levitation using the new levitation method was performed in the following two cases: (1) the upper magnet starts to operate when the bulk reaches the middle plane of the upper magnet; and (2) the upper magnet starts to

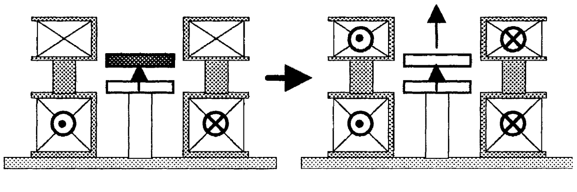

Fig. 4. New concept of continuous levitation.

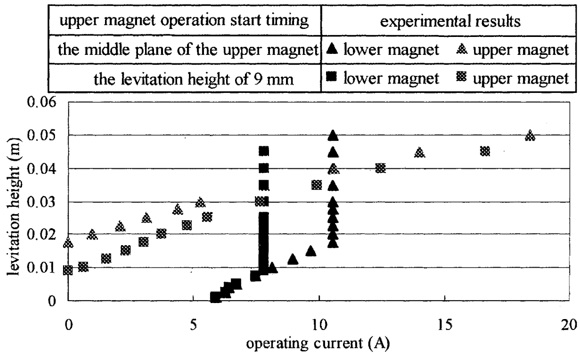

Fig. 5. Levitation height vs. operating current.

operate at the levitation height of 9 mm, i.e. beneath the upper magnet. The experimental result at the magnet gap of 10 mm is shown in Fig. 5. As seen in Fig. 5, the levitation height can be remarkably improved by the continuous levitation as well as the levitation method shown in Fig. 2. Moreover, the continuous 'stable' levitation without the supporting plate could be also achieved in this method. Using this method, we tried to demonstrate the continuous levitation in a three-magnet system and succeeded the continuous stable levitation in the same manner as the two-magnet system.

4.2. Electromagnetic behavior

At the end of the field-cooling process, positive supercurrent flows in the azimuthal direction of the bulk. The negative supercurrent region gradually increases from the outside of the bulk with the operating current of the lower magnet; this means that lift increases with the operating current. After starting the operation of the upper magnet, the total magnetic field in the axial direction increases, while that of the radial direction decreases. The effect of the magnetic field in the axial direction, however, becomes larger than that of the radial direction in our experiment, so that the total lift continues to increase with the operating current of the upper magnet. This effect depends on the magnet gap, the magnitude of trapped field and the levitation height at which the upper magnet starts to be operated.

5. Conclusions

A new type of active-maglev system comprised of YBCO bulk and two electromagnets was designed for improving levitation height. The lift and the levitation height in the new system were compared with those of a single-magnet system as a function of trapped field. Continuous levitation was demonstrated and the following effects on the continuous levitation was investigated experimentally: (1) the gap between the upper and lower magnets; and (2) the levitation height at which the upper magnet starts to be operated. The maximum levitation height in the two-magnet system was remarkably improved by the continuous levitation. These results imply that the larger number of electromagnets, the more levitation height.

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