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Characteristics of Lift and Restoring Force in HTS Bulk

—Application to Two-Dimensional Maglev Transporter—

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***Abstract*—One of the advantages of magnetic levitation using high-temperature superconducting (HTS) bulk is that stable levitation can be achieved without any control systems. We have been investigating the electromagnetic behaviors of HTS bulk to realize a two-dimensional magnetic levitating transporter without any fixed guides. The characteristics of lift and stability are key parameters to design and optimize such a device. We measured the lift and the restoring force of a YBCO bulk, displaced by a distance in lateral direction, for various field-cooling conditions and permanent-magnet arrangements. Both lift and restoring force are closely related to the air gap in the field-cooling process, distance between the permanent magnets, number of permanent magnets, and permanent magnet arrangement, that is, external magnetic field distribution. The most suitable arrangement of permanent magnets depends on the required levitation height and the weight of the levitating part. It can be considered that the size of the levitating part and geometry are also very important to determine the optimal arrangement in the maglev device.**

***Index Terms*—magnetic levitation, transporting device, stability, trapped field, YBCO bulk.**

I. INTRODUCTION

High T_c superconductor, especially HTS bulk, has been used for magnetic levitation systems such as flywheel energy storage system, non-contact transport system, and so on [1], [2]. In a levitation system that uses HTS bulk, the restoring force by pinning effect works on the bulk against the displacement due to some disturbances. Therefore the levitation system can achieve stable levitation without any complex control systems. We have investigated and developed a two-dimensional magnetic levitating device which can move stably and freely in any directions of a plane. In such a levitation device, it is necessary to ensure a proper levitation height and stability. To realize the levitation device, the electromagnetic characteristics of the HTS bulk, such as lift and stability including their relationship, should be clarified. Although the characteristics of lift and restoring force against lateral displacement had been investigated in some samples [1]-[4], the dependences of lift and restoring force on trapped-field strength, and the relationship between the lift and the restoring force, both very important for the design and the optimization of levitation devices, have not been discussed in detail. Therefore, we prepared six types of samples comprised of disk-shape YBCO bulk and some rectangular parallelepiped permanent magnets. The lift and the restoring force are measured as a function of air gap in the field-cooling process.

II. CONCEPT OF TWO-DIMENSIONAL MAGNETIC LEVITATING TRANSPORTER

Although HTS bulk has been applied to various types of magnetic levitating systems, most of them are used either in a static state or with one-dimensional movement, that is, the levitating body moves in one-direction [2]. We are aiming to achieve the magnetic levitating device used for two-dimensional movement; we call it "two-dimensional maglev transporter". The concept of the two-dimensional magnetic levitating device and a small trial model are shown in Figs. 1 and 2, respectively.

The model device is mainly composed of HTS bulks and permanent magnets. The upper part, levitating part, and the lower part are connected magnetically; this means that the levitating part can move together with the lower part's movement without any contacts between both parts. The lower part can be also driven by remote control system. Therefore, this device can be used without spatial restrictions.

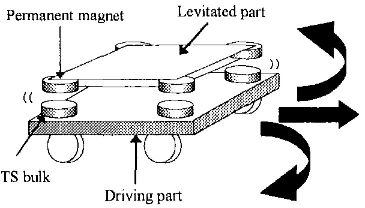

Fig.1. Schematic drawing of "two-dimensional magnetic levitating transporter".

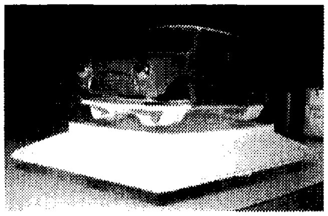

Fig.2. Trial small model.

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Based on the above advantages, we have been considering to apply this device to not only industrial field but also entertainment or amusement field.

In this trial model, we set HTS bulks and permanent magnets to the driving (lower) part and the levitating (upper) part, respectively, although it is possible to adopt the HTS bulks in the levitating part and the permanent magnets in the driving part. To realize the smooth drive and the stable levitation of the levitating part, proper magnitude of lift and restoring force against some disturbances must be ensured. Therefore we tried to investigate the fundamental characteristics of the levitating device, especially the dependence of the lift and the restoring force on the trapped-field strength.

III. EXPERIMENT

The axial air gap between HTS bulk and permanent magnets is a very important factor in a magnetic levitating device, and it depends on the weight of the levitating part and the magnitude of lift. Tilt and lateral stability of HTS bulk also play a key role for the stable levitation in the levitating device. Tilt stability chiefly depends on the trapped-flux strength; the larger trapped field, the more stable levitation. Lateral stability, however, is closely related to not only the trapped-flux strength but also the external magnetic field distribution. This means that the lift and lateral stability is more closely related to the permanent magnet arrangement than tilt stability. To investigate the influence of the permanent magnet arrangement on the lift and lateral stability, we prepared six types of samples with different magnetic-pole arrangement. In the samples, we measured the lift and the restoring force for various field-cooling conditions.

A. Arrangements of HTS Bulk and Permanent Magnet

The HTS bulk used in experiments is a disk-shaped YBCO bulk with 15 mm in diameter and 10 mm in thickness. Nd-B-Fe type of permanent magnet, a rectangular parallelepiped with a base 4 mm×4 mm and a height of 8 mm, is adopted as a component of the levitating part. The strength of magnetic flux density on the top surface of the permanent magnet is about 0.40 T. To investigate the dependences of: (1) number of permanent magnets; (2) distance between permanent magnets; and (3) relative position of HTS and permanent magnets, four or eight permanent magnets are employed to make six types of arrangements shown in Fig. 3. In Fig. 3, the distance between any two permanent magnets is set to be 4 mm in Type-C and 8 mm in Type-D, E and F.

B. Experimental Setup

The experimental setup for the lift and the restoring force measurements is schematically drawn in Fig. 4. The load cell is used for the lift and the restoring force measurements and the permanent magnets are fixed to the load cell. The permanent magnets can move in the vertical direction, that is, the air gap between the HTS bulk and the permanent magnets can be changed. The HTS bulk is fixed on the bottom of the vessel and immersed in liquid nitrogen. The distance in lateral direction between the HTS bulk and permanent magnets can also be changed by moving the vessel.

C. Measurements

Before the lift and restoring force measurements, the following field-cooling process was performed: (1) fix the HTS bulk on the bottom of vessel; (2) attach permanent magnets to load cell as a function of air gap in the range of 1 mm to 5 mm; and (3) let the HTS bulk become superconducting in liquid nitrogen. Then the lift and the restoring force were measured according to the following steps.

<lift>

(1) measure lift at the same air gap as that of the field-cooling process.
(2) let the air gap reduce and measure the lift at intervals of 0.5 mm until the minimum air gap of 0.5 mm.
(3) let the air gap increase and measure the lift at intervals of 0.5 mm until the air gap of field-cooling process.

<restoring force>

(1) measure restoring force at the same air gap as that of the field-cooling process.
(2) move the vessel in the lateral direction and measure the restoring force at intervals of 1 mm while maintaining the initial air gap between HTS bulk and permanent magnets. Note that the vessel is moved in the x-direction in Fig. 3.

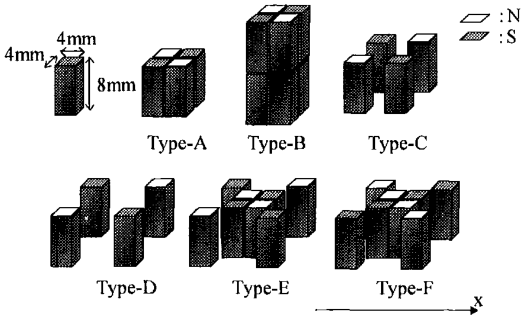


Fig. 3. Six types of samples with different magnetic-pole arrangements.

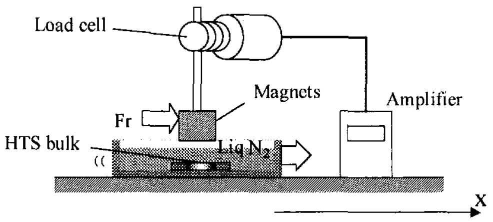
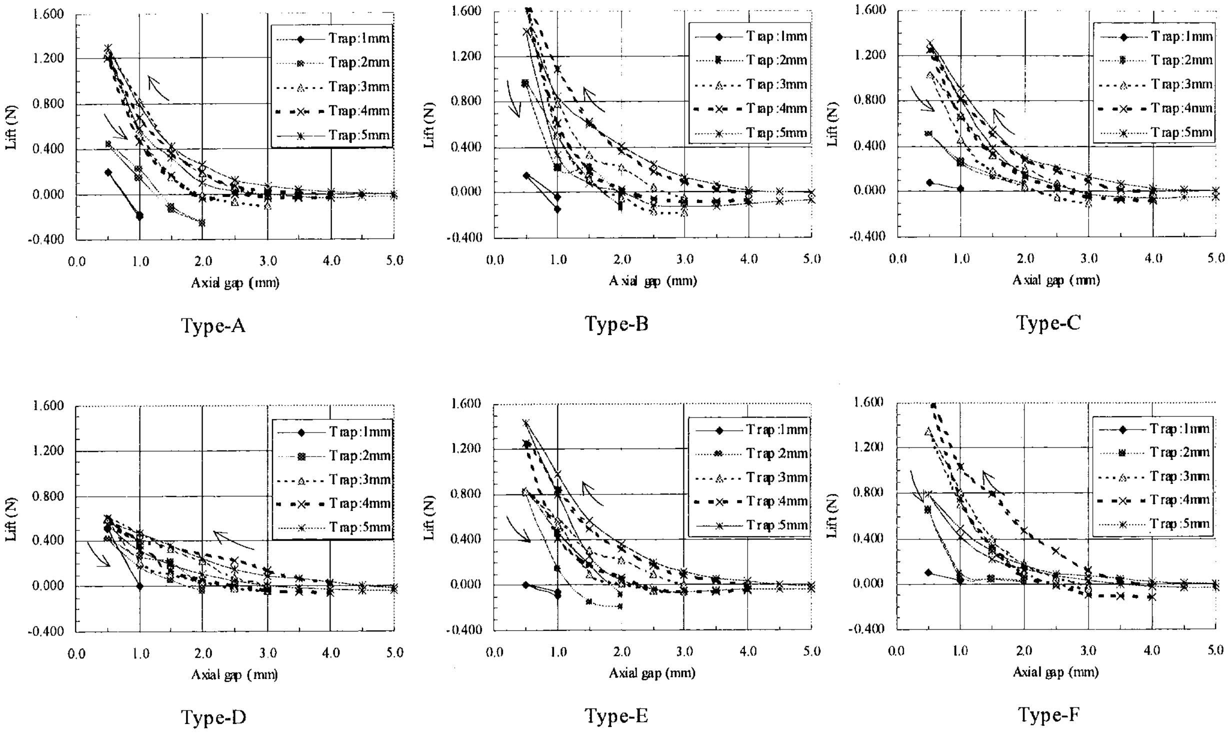


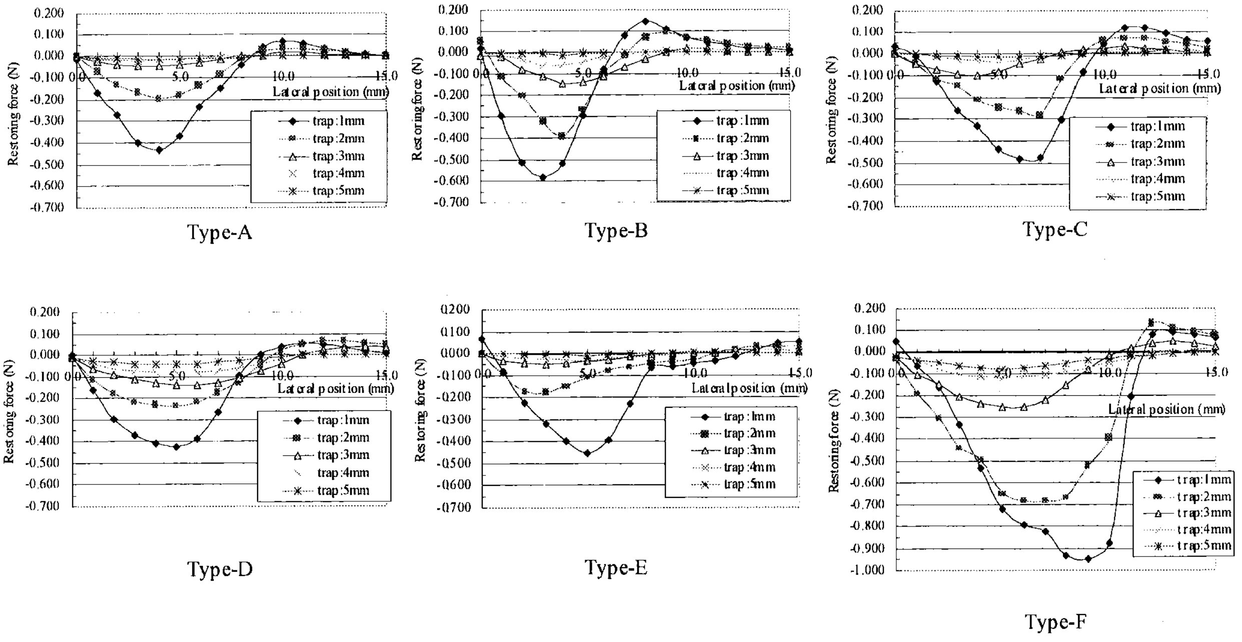
Fig. 4. Experimental setup for lift and restoring force measurements.



Type-A Type-B Type-C

Type-D Type-E Type-F

Fig.5. Lift for various magnetic-pole arrangements.



Type-A Type-B Type-C

Type-D Type-E

Type-F

Fig.6. Restoring force for various magnetic-pole arrangements.

IV. RESULTS AND DISCUSSION

A. Lift

Although the experimental results of lift can be interpreted variously, we investigate and compare them from the following points of view: (1) the magnitude of lift at a certain levitation height; and (2) the maximum levitation height at the certain weight of the levitating part, that is, a certain lift. The experimental results of lift in the six samples of permanent magnet arrangement as a function of air gap in the field-cooling process are shown in Fig. 5. As seen in Fig. 5, a hysteresis loop of the measured lift was observed in all samples; the lift in the process of reducing air gap is larger than that of increasing air gap. In most of the samples, the lift gradually decreases, and its rate decreases with decreasing air gap. The most suitable air gap for the field cooling process which gives the maximum lift exists between 4 mm and 5 mm, while the gap depends on the permanent magnet arrangements. The difference in the results of Type-E and Type-F implies that regardless of the field-cooling condition, the difference of magnetic field distribution due to the permanent magnet arrangement affects the lift significantly. From the point of view (1), it is observed that Type-B, E and F have larger lift than those of Type-A, C and D only in small air gaps. It can be considered from the results that the most suitable arrangement is Type-F and the lift increases with the number of permanent magnets and it is independent of their arrangements in small air gaps. From the point of view (2), however, the most suitable arrangement, independent of the magnitude of lift, can be considered to be Type-C. This means that the preferable arrangement, Type-C, differs from those of (1), Type-F.

B. Restoring Force

The characteristics of restoring force are very important to achieve stable levitation in the device with movement because the levitating part is accelerated in the same direction as the external force. The levitation part must be returned to its original equilibrium position against the external force. In the case of changing the movement direction frequently, the lateral stiffness, that is, the magnitude of maximum restoring force becomes a key parameter. In regard to acceptable energy for maintaining stable levitation, however, the acceptable distance of displacement also becomes very important in addition to the lateral stiffness; sometimes more important than the magnitude of maximum restoring force. Measurement results of the restoring force in the six samples as a function of air gap in the field-cooling process are shown in Fig. 6. In all samples, the restoring force (< 0) has a peak and the minus sign of the force is turned into plus at a larger distance than that of the peak. The peak of restoring force depends on the air gap in the field-cooling process; the larger restoring force is obtained in the smaller air gap. Regarding the absolute value of the restoring force, the big difference is not observed in Type-A, C and D, especially no big difference between Type-C and D as seen in Fig. 5. This means that the distance between permanent magnets is not a big factor in this experiment. On the other hand, a much bigger difference of the restoring force than the lift between Type-E and F is observed. This result implies that the permanent magnet arrangement is much more important in restoring force than in lift. The restoring force is apparently improved by increasing the number of permanent magnets in the vertical direction. From the point of view of acceptable distance, the suitable arrangements change in each air gap, particularly in small air gaps. From the point of view of maximum restoring force and acceptable energy, however, the most suitable arrangement becomes Type-F, and it is independent of the air gap.

Although it is very difficult to determine the most suitable arrangement only from these results, it would be Type-F in the six samples with respect to both lift and lateral stability. It may be necessary, however, to have further investigations about the most suitable field-cooling conditions, because the small air gap is preferred in lateral stability, while the large air gap is preferred in lift.

V. CONCLUSIONS

The characteristics of lift and restoring force in the magnetic levitating device comprised of HTS bulk and permanent magnets, for the application to the two-dimensional magnetic levitating transporter, are investigated experimentally. Lift and restoring force are measured in six types of permanent magnet arrangements as a function of the air gap in the field-cooling process. Both lift and restoring force are closely related to the air gap in the field-cooling process, the distance between the magnets, number of permanent magnets, and permanent magnet arrangement. These experimental results imply that trapped-field strength and external magnetic field distribution are key factors in such levitating devices. It is important to investigate these characteristics experimentally in the case that: (1) the lift is balanced with the own weight; and (2) the levitating device moves with changing velocity. Moreover, numerical investigation of magnetic field distribution around the levitating device and electromagnetic behavior within HTS bulk should be performed to determine the most suitable field-cooling condition and the best arrangement of HTS bulk and permanent magnets.

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