Numerical Analysis of Levitating Force Using Magnetic Shielding Effect of YBCO Plates

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Abstract—A magnetic levitation system using magnetic shielding effect of HTS bulk is studied. The system is constructed by permanent magnets, zero-field-cooled superconducting bulks and ferromagnetic rails, and lift force stability is obtained from magnetic field that is generated by the permanent magnet and is shaped by the superconducting bulks. In previous studies, we showed characteristics of lift force and stability about a basic model which had a small ferrite permanent magnet, three YBCO bulk superconductors and a short ferromagnetic bar. Now, improving the basic model, we found new models which have better characteristics of lift force by numerical analysis using 3D Integral Element Method (IEM). The new models are reported.

Index Terms—Lift force stability, magnetic levitation, magnetic shielding effect, YBCO bulk.

I. INTRODUCTION

MAGNETIC levitation systems using HTS bulk have high potential and various types of levitation system have been studied [1]–[3]. The systems use pinning force of the HTS bulks that enables to trap or shield magnetic field. One of the most important points about the systems is to generate stable levitation force without any active control system. This point can provide safety levitation when power failure is happened, and less power consumption is achieved for levitation.

We have been focusing magnetic shielding effect of the HTS bulk, and we have been studying a magnetic levitation system using the effect [4]–[6]. In this study, only the stability of vertical direction has been studied among the stabilities of levitation, because this study is still basic stage. A basic model of the system consists of a permanent magnet, HTS bulks, and a ferromagnetic bar. The ferromagnetic bar as a rail is fixed by structures which has to be made from nonmagnetic materials. And, the magnet and the HTS bulks are placed in a transporting vehicle. The magnetic field generated from the permanent magnet is shaped by the HTS bulks, and the field reaches the ferromagnetic bar. The magnetic field nearby the HTS bulk is reduced, because the magnetic field is shaped by the HTS bulks. The lift force increases when the vehicle goes away from the rail, and the vehicle can return to the previous position. Therefore, a stable lift force without any active control system can be achieved. Another advantage of this system is to simplify the rail structure. The simple structure of rail allows reducing construction costs.

We have improved the basic model of the magnetic levitation system, and we find new models that have better characteristics of lift force than previous models. The characteristics of lift force are evaluated by numerical analysis. ELF/MAGIC that is a 3D nonlinear magneto-dynamic analysis software with IEM (Integral Element Method) is used to calculate the lift force. In this paper, three improved models are presented. In this system, characteristics of the lift force stability and the weight of materials are key parameters. The keys of the improved models and the basic model are discussed.

II. MAGNET LEVITATION SYSTEM

A schematic illustration of the basic model about the system is shown in Fig. 1. And top view of materials is shown in Fig. 2. Length of the permanent magnet is defined as $X_m$, and width of it is defined as $Y_m$. The HTS bulk is zero-field cooled and acts as a diamagnetic material. Basically, the permanent
magnet is set to be shorter and wider than the HTS bulk. If the magnet is narrower than the HTS bulk, the flux reaches hardly the ferromagnetic bar. If the magnet is longer than the HTS bulk, the flux is not shaped by the HTS bulk and directly reaches the ferromagnetic bar and the lift force stability is not obtained.

An example of the characteristic of lift force and stable region are shown in Fig. 3. \( G \) is the distance between the vehicle and the ferromagnetic bar. There is 2.5 mm gap between the bottom of the surface of the ferromagnetic bar and the top of the surface of the HTS bulk when the \( G \) is 0 mm. In the previous experiment, the HTS bulk and the magnet was fixed in a liquid nitrogen vessel which was used as a vehicle. The 2.5 mm gap is the thickness of the vessel. The HTS bulk and the magnet is cooled by liquid nitrogen in the vessel. Stable region is defined as the area which provides lift force stability. When the vehicle is in this region, the lift force keeps decreasing as the \( G \) is decreased. On the other hand, the lift force keeps increasing as the \( G \) is increased. Thus, in this region, the vehicle can return stable point of levitation.

III. NUMERICAL ANALYSIS

Numerical analysis is performed with 3D nonlinear magneto-dynamic analysis software ELF/MAGIC using IEM (Integral Element Method).

A variable magnet element is used as the model for the permanent magnet. The magnetic field is set to the \( z \) direction. The coercivity of the element is set to 3.18 \( \times 10^7 \) A/m, and the remanence flux density is set to 0.4 T.

A magnetic body element is used as the calculation model for HTS bulk and ferromagnetic materials. The magnetic permeability of the element for HTS bulk is nearly zero. It means that the element for HTS bulk simulates Meissner materials. In previous study, there is small difference between the characteristic of lift force calculated with the Meissner state model and the characteristic measured by experiment about the basic model. Therefore, we use the Meissner state model which can be calculated faster than pinning state models. The magnet body element for the ferromagnetic bar and other ferromagnetic materials are given nonlinear \( H \rightarrow B \) curve. The \( H \rightarrow B \) curve is set to a general characteristic of iron for structural materials.

A. Basic Model

The basic model consists of one permanent magnet, one HTS bulk, and one ferromagnetic bar. And specifications of materials in the basic model is listed in Table I. Although the HTS bulk is one big plate in this specification sheet, several small plates could be spread and be substituted in experiment.

1) Model A - Changing Shape of Permanent Magnet: The first improvement of the basic model is to change the shape of the permanent magnet. This model is named model A. The specifications of the materials of the model A is listed in Table II. The purpose of changing the shape of the magnet is to increase stable region. The stable region is made from the HTS bulk to the ferromagnetic bar, but the HTS bulk can not shape the magnetic field efficiently when the magnetic field which reaches the HTS bulk is diffused. The magnetic field nearby the HTS bulk in the basic model is much diffused, so the stable region of the basic model is small as 7 mm. Therefore, using bigger magnet, more stable region would be gotten because magnetic flux from the magnet reaches the HTS bulk more vertically, and magnetic flux is shaped more efficiently by the HTS bulk.

2) Model B - Multi Sets of HTS Bulk and Ferromagnetic Bar: The second model named model B consists of one big magnet and several sets of the HTS bulk, and the ferromagnetic bar. A schematic illustration of the model B with three sets is shown in Fig. 4. And the specifications of materials of the model B is listed in Table III. The model B is an improvement of the model A. The model A got larger stable region by enlarging the magnet. And if width of stable region mainly depends on the ratio of widths of the HTS bulk and the ferromagnetic bar is added because the ratio of widths of the magnet and each HTS bulk does not change. Lift force can be increased when the set is added. The self-weight of the model increases by the weight of the HTS bulk when the set is added, because the size of the magnet is not changed and the ferromagnetic bar is not related to the self-weight. The HTS bulk is much lighter than the magnet, because the HTS bulk is thin and small. Therefore, the lift force per unit weight would increased and large stable...
Fig. 4. Schematic illustration of the model B with three sets of HTS bulk and ferromagnetic bar.

**TABLE III**

**SPECIFICATIONS OF THE MATERIALS OF THE MODEL B**

<table>
<thead>
<tr>
<th>Material</th>
<th>Size $x \times y \times z$ (mm)</th>
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<tr>
<td>Permanent magnet</td>
<td>$60 \times 100 \times 10$</td>
</tr>
<tr>
<td>HTS bulk</td>
<td>$120 \times 30 \times 2$</td>
</tr>
<tr>
<td>Ferromagnetic bar</td>
<td>$360 \times 6 \times 6$</td>
</tr>
</tbody>
</table>

Fig. 5. Schematic illustration of the model C. (a) shows perspective view of the model C. (b) shows shape of ferromagnetic material which covers HTS bulk.

region would be obtained when the sets of HTS bulk and ferromagnetic bar are added with the model A.

3) **Model C - Adding Bent Ferromagnetic Material**: The final improvement is to add a ferromagnetic material whose both ends are bent. The perspective view of the second model named model C is shown in Fig. 5. The ferromagnetic material draws the magnetic field and supports HTS bulk shaping magnetic field. Therefore, the load of HTS bulk could be reduced, and more magnetic flux could reach the ferromagnetic bar. The sizes of the HTS bulk, the magnet and the ferromagnetic bar are same as the basic model.

V. RESULTS

A. **Model A**

The characteristics of lift force about the model A and the basic model is shown in Figs. 6 and 7. Fig. 6 shows the comparison of the characteristics of lift force when $X_m$ (length of the magnet) is 20 mm. The peak value of lift force and the stable region increases with increasing $Y_m$ (width of the magnet), but there are almost same characteristics of lift force when $Y_m$ is over 100 mm. This is because more magnetic flux can reach the ferromagnetic bar when $Y_m$ is larger, but there is a limit of increasing the magnetic flux by increasing $Y_m$. Therefore, it is not efficient to enlarge $Y_m$ too much.

Fig. 7 shows the characteristics of lift force which is compared on $X_m$. When $X_m$ becomes larger, the peak value of lift force and the stable region increases. The magnetic field nearby the HTS bulk becomes more vertically when $X_m$ is large. Because the magnetic field is shaped efficiently when the field nearby the HTS bulk is almost vertical, and then better characteristic of lift force is obtained when $X_m$ is large.

B. **Model B**

Fig. 8 shows the characteristic of lift force about the model B. The peak value of lift force increases without decreasing the
force per unit weight and the stable region. Most of the new models have bigger lift force per unit weight and larger stable region than the basic model. Especially, the model $B$ has good characteristics and still has potential for increasing lift force by adding another set of the HTS bulk and the ferromagnetic bar. Because the improvement of the model $A$, $B$ and $C$ do not interfere with each other, all of them can be added to the basic model at once and bigger lift force and larger stable region would be obtained.

In this study, we used the ferrite magnet for the comparison with the basic model and the previous study, and the lift force per unit weight is very small. However, the lift force will much increase when a SmCo or NdFeB magnet is used. Therefore, it is thought that enough lift force could be obtained when the magnet of the new models are changed.

VII. CONCLUSION

New improved models of a magnetic levitation system using magnetic shielding effect of HTS bulk are evaluated by numerical analysis. The system has levitation stability without any active control system, shaping magnetic field by magnetic shielding effect of zero-field-cooled HTS bulk. Most of the new models have better characteristics of lift force in comparison with previous models, and especially a new model which has multi sets of HTS bulk and ferromagnetic bar, named the model $B$, has the biggest lift force and large stable region in these models. The model $B$ still has potential to be improved, and much better characteristics of lift force could be provided by improving the model $B$. These new improvements do not conflict with each other. Therefore applying all of these new improvements, a better model could be found.

REFERENCES