Shape Dependency in Levitation System Using HTS and Soft Magnetic Material

Mojtaba Ghodsi, Toshiyuki Ueno, and Toshiro Higuchi

Precision Machinery Department

The University of Tokyo

7- 3-1,Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan

ghodsi@intellect.pe.u-tokyo.ac.jp

Hidekazu Teshimab and Hosei Hiranob

Nippon Steel Corporation

20,1, Shintomi, Futtsu-city, Chiba , 293-8511, Japan

***Abstract*- It is well known that a ferromagnetic material can be levitated by a field cooled superconductor. This paper presents a new method to model the pinning effect by using a Finite Element Method (FEM). Being compared with the experimental results the validity of the presented method is verified. Furthermore, the effect of pole shape on the stiffness of the levitation system is investigated. The relationship between the attractive force and the air gap was numerically analyzed and experimentally measured at both, room temperature (RT) and superconductivity state (77 K). Results obtained from FEM modeling show a good agreement with experimental results. It was found that the stiffness of the system becomes almost double (6 N/mm) when the ring pole is used instead of cylindrical pole with the same surface area.**

Index Terms- Pinning Effect, HTS, Pole Shape, FEM

1. INTRODUCTION

Magnetic levitation is one of the attractive applications of bulk high temperature superconductors (HTS). On account of the diamagnetic property of superconductive material, a permanent magnet (PM) can be levitated over HTS [1]. Although passive levitation and high levitation force are two considerable advantages of this conventional suspension system, magnet rail in public transportation is very expensive. Tsutusi proposed levitation of ferromagnetic yoke using a permanent magnet and bulk HTS, operated in liquid-Nitrogen [2]. Both the levitation force and the stiffness of presented system were too small for practical applications. Tsutsui believed that positive stiffness to realize the levitation is attributed on escape of flux, but the actual mechanism has not been supported by experimental results [2]. So far, we highlighted the role of the thickness of the HTS sample in this levitation system and a levitation of 8.6 kg mass with 3.5 N/mm in stiffness was demonstrated [3]. Furthermore, the main reason of this levitation system was manifested by novel experimental method [4].

In this research a new method of modeling of pinning effect by a commercially available FEM software tool is presented. Moreover, since the robustness against the external disturbance plays an important role in this passive levitation system, the effects of pole shape on the stiffness of the system are investigated. To serve this purpose two patterns of pole, ring and cylindrical, are used to measure the relationship between force and air gap in this levitation system.

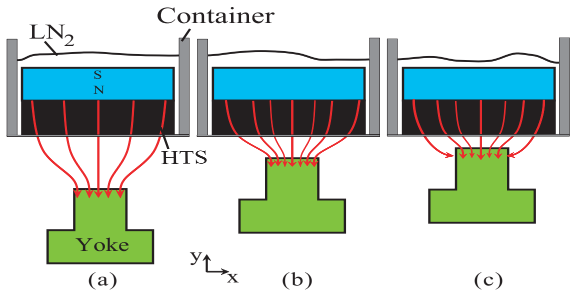


Figure 1. Principle of passive levitation of soft magnetic material

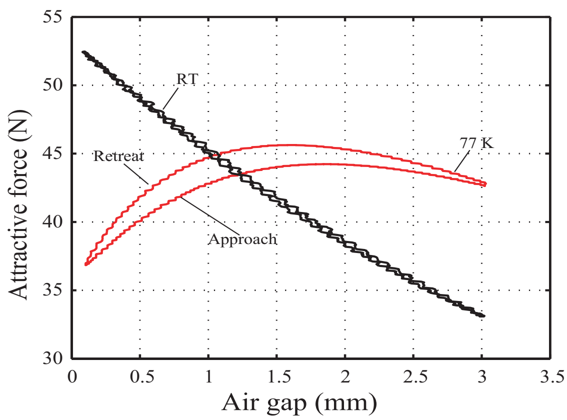


Figure 2. Attractive force vs. air gap at RT and 77 K; HTS thickness= 10 mm, Ring pole

2. PRINCIPLE OF LEVITATION

The basic geometry of this levitation system is shown in Fig. 1. The vertical magnetic force on an unsaturated iron body of high permeability in a magnetic field is given by the simplified Maxwell stress formula [5]:

$$F = \int_A \frac{1}{2\mu_0} B_n{}^2 dA \qquad (1)$$

where B_n and A are the normal magnetic flux density and face surface area of yoke.

The magnetic flux can be trapped in type-II of high temperature superconductor (HTS) which is called "pinning effect". Although the fluxes are pinned by impurities inside of the HTS sample, however, the freedom of fluxes expels from the surface of HTS is limited. When the cylindrical yoke approaches to HTS from Fig. 1 (a) to (b), the trapped magnetic fluxes emanated from the surface of HTS gather toward the yoke and the attractive force increases. However, as the yoke approaches closer to the surface of HTS (Fig. 1 (c)), the magnetic fluxes which pass through the face surface of yoke will decrease and some of the fluxes will enter from the side surface of the yoke. Thereby, the reduction of the normal flux density causes a decrease of the attractive force (Eq. (1)). As a result, a positive stiffness in the curve of attractive force vs. gap allows the stable levitation of the yoke. By using this idea, a transportation system can be constructed with low cost, e.g. the rail can be constructed with iron.

For instance, the relationships between the attractive force and the gap at 77K and RT in approach/retreat cycle are shown in Fig. 2. It is obvious that in case of RT, the attractive force increases when the gap decreases. This system at RT is intrinsically unstable, because the stiffness over the complete range of the gap is negative. In contrast, the general shape of this relationship at 77 K is different. As the gap is 3mm, the force is 42.5 N and it gradually increases to 44 N in 1.8 mm gap. By reducing the gap, the force decreases to 37 N in 0.1 mm gap. In retreat, the force increases to 45.5 N in 1.6 mm and decreases to initial value in 3 mm. Therefore, the positive stiffness in the small air gap (<1.6 mm) allows a stable passive levitation.

3. MODEL OF PINNING EFFECT BY FEM

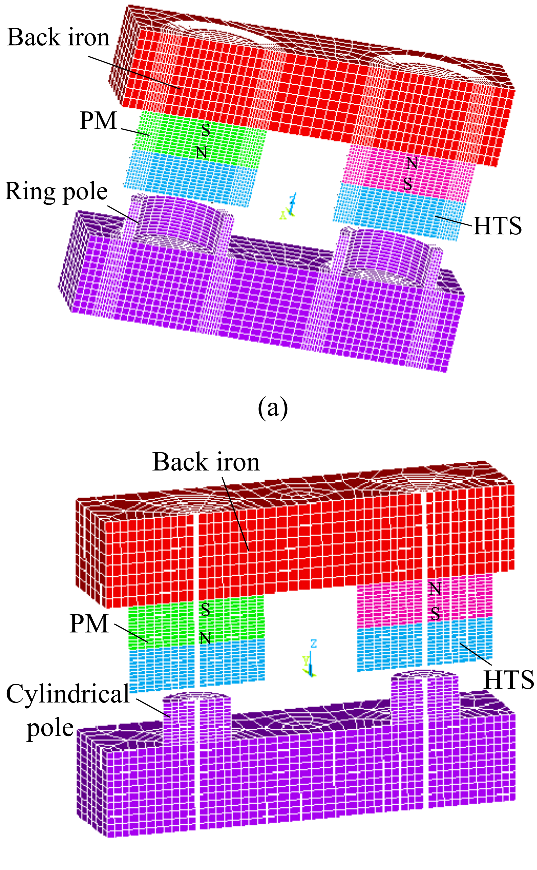
The design and optimization of levitation system structure using HTS is a costly and time-consuming process. It can be reduced by software tools able to describe the superconductivity phenomenon. On the other hand, the superconductor element and Hystersis effect are not implemented in the present commercially available field analysis tools.

In our previous research [4] we show that in superconductivity state the pinned fluxes in the HTS samples remain approximately constant when the yoke approaches/retreats to the HTS. It means

$$\frac{\partial \phi_{HTS}}{\partial (gap)} = 0 \Rightarrow S.\frac{\partial B_{HTS}}{\partial (gap)} = 0 \quad , \qquad (2)$$

where ϕ_{HTS} and B_{HTS} are the flux and flux density trapped in the bulk superconductor, respectively. S denotes the surface area of bulk HTS.

Using the magnetic vector potential A, the governing



(b)

Figure 3. Modeling and meshing by ANSYS; (a) Ring, (b) Cylindrical

equation for a 3-D analysis could be found as

$$B_{HTS} = \nabla \times A \,. \qquad (3)$$

Replacing (2) in (3) causes

$$\nabla \times \frac{\partial A}{\partial gap} = 0 \quad . \qquad (4)$$

To avoid long term program development, the general purpose FEM program ANSYS is customized for the simulation of the pinning effect in the HTS. Equation (4) shows this fact that the vector potential of each node inside the HTS sample, A_n, is constant during the approach and retreat cycles. Therefore,

$$A_n = (A_x, A_y, A_z) = Const. \quad . \qquad (5)$$

When the vector potential is known, it can be considered as a load condition.

The magnetic fluxes are trapped inside the HTS samples during cooling process. As will be explained in the next section, the cooling is done when the distance between HTS and yoke is 3 mm. Thereby, the fluxes correspond to the 3 mm air gap are trapped in the HTS samples. To simulate the pinning effect the following guideline must be undergone:

- Since the model is symmetric, create only half of the 3-D model and mesh it (Fig. 3).

- Apply the flux parallel condition as a boundary condition to the cut cross section.
- Analyze the generated magnetic model when the air gap is 3 mm and save the vector potentials of all HTS's nodes.
- Apply the obtained vector potential results as a load condition to all corresponding nodes of HTS and repeat the analysis for different air gaps (less than 3 mm).

Figure 3 shows a schematic view of modeling and meshing of levitation system. To investigate both the validity of this model and effect of yoke shape, two patterns of ring and cylindrical poles are modeled. The specifications of the exploited bulk HTS samples and the PM are mentioned in Table 1.

4. EXPERIMENTAL DETAILS

It seems that the geometrical shape of the pole of movable yoke has significant effects on the stiffness of this levitation system. Thereby, the behavior of attractive force vs. air gap when movable yoke equipped with ring and cylindrical poles is investigated in both, room temperature (RT) and superconductivity state (77 K). The basic configuration of the experimental setup is shown in Fig 4. The magnetic circuit comprises of two main parts, stationary and moved parts. Stationary part consists of two bulk disk of HTS attached by two permanent magnets (PMs) to a back iron yoke. The c-axis of the HTS samples is parallel to the magnetization axis of the PMs. The movable yoke is made of iron with cylindrical and ring poles, whereas, the area of face surface of both poles are equals. Therefore, the stationary and the moved parts make a close magnetic flux loop. The relationship between the attractive force and the air gap is measured by load cell and displacement laser sensor (Keyence LC-2440) respectively, in approached/retreated cycles. The measurement is repeated in superconductivity state. To serve this purpose the cryostat is filled with the liquid nitrogen when the yokes are placed in the 3 mm air gap.

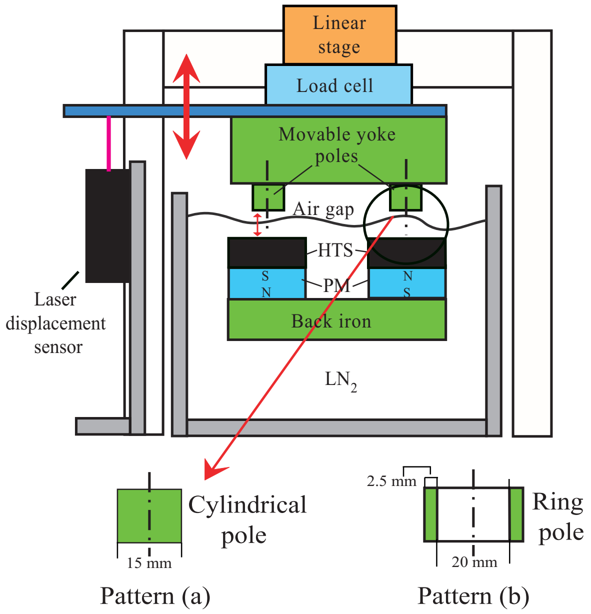


Figure 4. Schematic configuration of experimental setup; (a) cylindrical pole, (b) ring pole

Table 1. The specifications of components

Items	***Specifications***	
Permanent Magnet (PM)	NdFeB,	
	B_r=1.24T	
	H_c=984000 A/m at RT	
	Temp. Coeff. of B_r= -0.1 %/℃	
	ϕ = 30 mm, t = 10 mm	
HTS (DBCO)	$DyBa_2Cu_3O_{7-x}$	75.0wt%,
	$Dy_2Ba_1Cu_1O_5$	24.50wt%
	Pt	0.5 wt%,
	ϕ = 30 mm, t= 10 mm	

5. RESULTS AND DISCUSSIONS

The relationship between attractive force and air gap measured and simulated at RT for cylindrical and ring poles is shown in Fig. 5. The general shape of curves is similar in which decreasing of the gap causes increase of force. Since the flux leakages in the simulated model are ignored, the force values of simulation results are higher than experimental results. This system at RT is intrinsically unstable, because the stiffness over the complete range of the gap is negative.

Attractive force as a function of air gap at 77 K for magnetic circuits equipped with different pole patterns is shown in Fig. 6. The reduction of the attractive force in the small air gap causes a positive stiffness. Like the RT results, because of flux leakage the force values obtained from the simulation is higher than the experimental results. The numerical results show that the maximum force for ring and cylindrical happens at 2 and 1.6 mm, respectively. While, the experimental results show that it happens at 1.6 and 1.3 mm. Furthermore, the numerical results predicate the considerable increase of stiffness by using the ring pole instead of the cylindrical pole. This enhancement is verified by the experimental results. The stiffness of system by ring pole reaches to 6 N/mm which is approximately two times of system's with cylindrical pole. Therefore, 3-D simulation results at RT and 77 K show a good agreement with the experimental results. It is necessary to mention two points. The first is that, in simulation of PM at 77 K the value of residual flux density (B_r) must be considered 1.47 T, whereas, it is 1.24 T at RT. The last is impossibility of Hystersis modeling by ANSYS software.

The presented modeling method provides good results which can be used to predict the force behavior of system. Now we use this modeling technique to verify the principle of this levitation system explained former. Regarding to Eq. (1) the attractive force will increase, if the average value of normal flux density increases. Figure 7 shows the basic configuration and flux distribution of the generated model.

To realize the normal flux density (B_z) on the pole surface, B_z values obtained from numerical analysis are

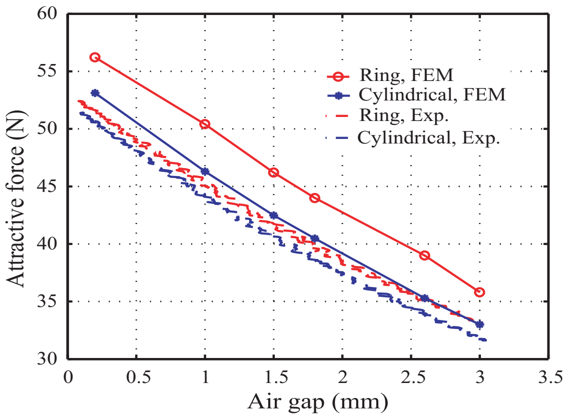


Figure 5. Attractive force vs. air gap at RT; HTS thickness = 10 mm, Cylindrical and Ring poles

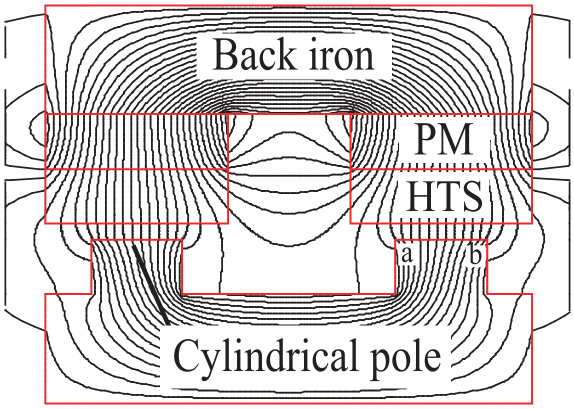


Figure 7. Configuration and flux distribution with cylindrical pole

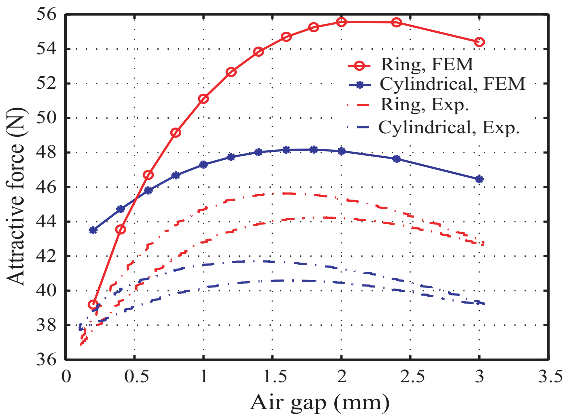


Figure 6. Attractive force vs. air gap at 77 K; HTS thickness = 10 mm, Cylindrical and Ring poles

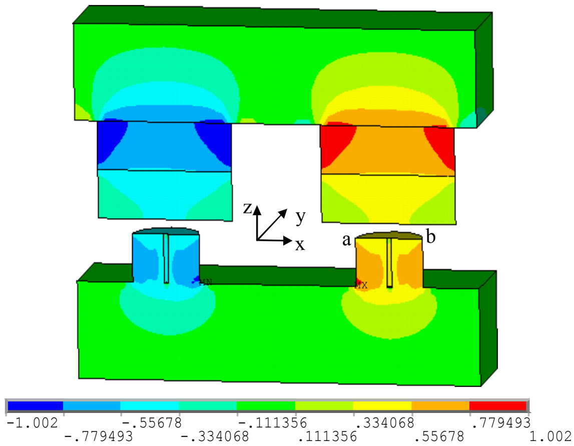


Figure 8. *Z* component of magnetic flux density (B_z), HTS=10 mm, gap= 3 mm at RT, Unit is Tesla

monitored on a line (diameter) of the cylindrical pole denoted by ***ab*** (Fig. 7). The analysis is done when the gap is 3, 2, 1 and 0.2 mm. As an example, normal flux density (normal to the pole yoke) when the gap is 3 mm at RT is shown in Fig. (8).

The values of magnetic flux density on ***ab*** line (B_z) at RT is shown in Fig. (9). Because of flux concentration on edges of pole, flux density decreases from the sides toward the center of pole. The average value of B_z at RT increases from 0.38 T to 0.5 T when the gap decreases from 3 mm to 0.2 mm. It is obvious that, gap reduction causes increase of B_z and consequently, the attractive force will increase. This analysis is repeated at 77 K (Fig. 10). As it was expected, average value of B_z in 3 mm increases to 0.45 T. It increases to 0.46 T for 2 mm gap and it reduces to 0.41 T when the gap is 0.2 mm. In the other words, the reduction of magnetic flux entering to the face surface of pole from 2 mm causes the positive stiffness in the small air gap.

Figure 10 demonstrates a useful point for pole shape design. We assume that the pole area is divided to two areas of central (3 mm<x<12 mm) and peripheral (x<3 mm and x>12 mm). By changing the gap, approximately the variation of *Bz* at the central part of pole is zero, whereas, a big variation of flux can be monitored at peripheral area. It means that, by increasing the peripheral area, the stiffness will increase. Thus, the stiffness of ring pole is considerably bigger than cylindrical pole.

6. CONCLUSIONS

We have studied the behavior of a field cooled HTS sample in the levitation system of a ferromagnetic material by the HTS. The validity of presented technique was verified by experimental results. The relationship between the attractive force and the air gap was numerically analyzed and experimentally measured at both, room temperature (RT) and superconductivity state (77 K). The results obtained from numerical analysis show a good agreement with experimental results. It was found that the stiffness of the system reaches to 6 N/mm with the ring pole, while it is about 3.5 N/mm for the cylindrical pole. The numerical results show that at superconductivity state, the magnetic flux entering through the pole is reduced when the gap decreases. Furthermore, it was found that peripheral area of the pole has the most effect on the stiffness of this levitation system.

References

[1] K. B. Ma et al, "Superconductor and Magnet Levitation Devices", Review of scientific instruments, Volume 74, , pp 4989-5017 (2003).

[2] Y. Tsutsui, A. Yamamoto, T. Higuchi, " Suspension of Soft Magnetic Materials Using High-T_c Superconductors", Proc.1st Int. Symp. LDIA , pp 259 (1995).

[3] M. Ghodsi, T. Ueno, T. Higuchi: "Improvement of Magnetic Circuit in Levitation System Using HTS and Soft Magnetic Material", IEEE Trans. Magn., 41, pp 4003(2005).

[4] M. Ghodsi, T. Ueno, H. Teshima, H. Hirano T. Higuchi: "The Characteristics of Trapped Magnetic Flux inside Bulk HTS in the Mixed-μ Levitation System", accepted by Physica C (2006).

[5] J.A. Stratton, Electromagnetic theory, pp 156-157, (1941).

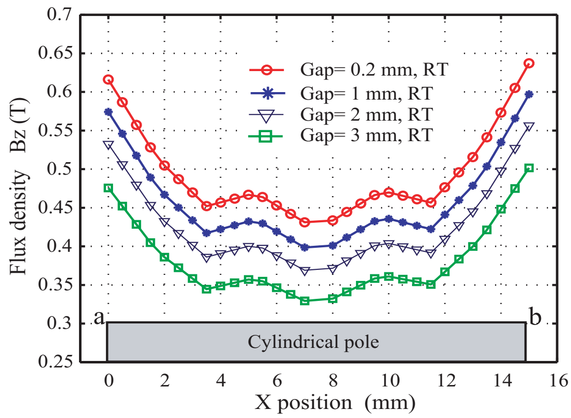


Figure 9. *Z* component of magnetic flux density (B_z) on the *ab* line in different gaps at RT

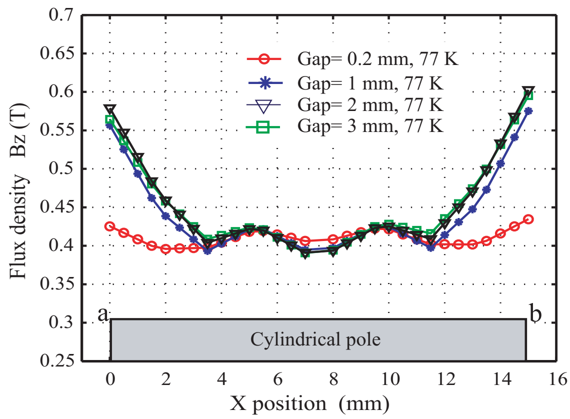


Figure 10. *Z* component of magnetic flux density (B_z) on the *ab* line in different gaps at 77 K