Magnetic Levitation System Using High Temperature Superconductor and Soft Magnetic Material

（高温超伝導体と軟磁性材料を用いた磁気浮上に関する研究）

ゴドシィ　モジタバ

Abstract

Superconductors are receiving significant attention from industries. They are used in a lot of machines the same as motors, actuators, flywheels, bearings, vibration isolator and convey systems. Magnetic levitation is one of the attractive applications of bulk superconductors (SC). On account of the diamagnetic property of superconductive material, a permanent magnet (PM) can be levitated over high temperature superconductor (HTS). Passive levitation and high levitation force are two considerable advantages of this conventional suspension system. An example of contactless conveys system can be found in toys in which a truck containing HTS is levitated over magnetic path. This suspension system can be used for public transportation system, but the cost would be high as the rail has to be made of permanent magnet. If low-carbon steel can be levitated by the HTS sample, the rail of convey system will be made of steel to reduce the cost considerably.

The theory of passive levitation of ferromagnetic material by diamagnetic material was presented by Braunbek in 1939. The levitation of ferromagnetic material has been proven useful for high speed ground transportation systems and bearing with high speed. A large body of research exists on the ferromagnetic levitation by superconductor. Some of these papers address the applications of low temperature superconductors (LTS) in levitation systems. In 1981, Joyce and Williams presented a new form of magnetic contactless suspension system known as a “mixed-mu” [JOY81]. In mixed-mu system a diamagnetic superconducting material is used for stability of low-carbon steel and made a great promise for different applications. Joyce believed that a diamagnetic material has the property of tending to exclude magnetic flux from its interior. In other words, at the surface of a strongly diamagnetic material the normal flux tends to zero because of super-conducting screens [JOY81]. The theoretical, computational, experimental works with a number of configurations have been summarized in [PAU84]. The advantages of levitation system by low-carbon steel rail refers to independency of lifting and stabilizing force from the vehicle speed and would be available over the whole range of speed (from rest to 400

km/h). To my knowledge since this system was cooled by liquid helium, the designed system was not manufactured for real applications.

The revolution in superconductor materials, discovery of HTS in 1986, directed the scientists toward using HTS in levitation systems. Several researches about application of HTS in levitation systems use the PM and present a very simple structure which is able to work by liquid nitrogen. Tsutusi and Hull proposed levitation systems which consist of a permanent magnet, bulk HTS and a levitated yoke operated in liquid-nitrogen [TSU94, HUL94]. Tsutsui claimed that because of "pinning effect" the force between the yoke and the HTS is an attractive force, but the actual mechanism of this levitation system was not supported by experimental results [TSU94]. However, Hull postulated that, because of the diamagnetic properties of the HTS, magnetization of the steel induces shielding currents in the HTS, resulting in a repulsive force between the HTS and the steel [HUL94]. Now, this question rises that what is the exact nature of force exerted between HTS and yoke. In this dissertation, I will try to find out the exact nature of force between ferromagnetic material and HTS. Additionally, the proof of the actual mechanism of the levitation system will help to find out the effective parameters in this levitation system.

Chapter 2 reviews different types of superconductor material. It is shown that, superconductors are mainly divided to type I and type II. Among type II, some significant properties of hard superconductors the same as "pinning effect" and those parameters which have direct effect on it are discussed. This chapter research demonstrates how higher critical current causes stronger pinning centers.

A literature review over the passive levitation mechanisms is presented in chapter 3. Here, the passive levitation of PM by HTS and Pyrolytic Graphite (PG) and some applications of passive levitation, for examples passive bearings, vibration isolator and maglev are described.

Chapter 4 discusses about levitation techniques in which ferromagnetic material are levitated by low temperature superconductor (LTS) and high temperature superconductor (HTS). Direction of this dissertation is towards the ferromagnetic levitation by the HTS. The basic geometry of this levitation system is shown in Fig. 1. The vertical magnetic force on an unsaturated low-carbon steel body of high permeability in a magnetic field is given by the simplified Maxwell stress formula [MAR04]:

$$F = \int_S \frac{1}{2\mu_0} {B_n}^2 dS \, , \qquad (1)$$

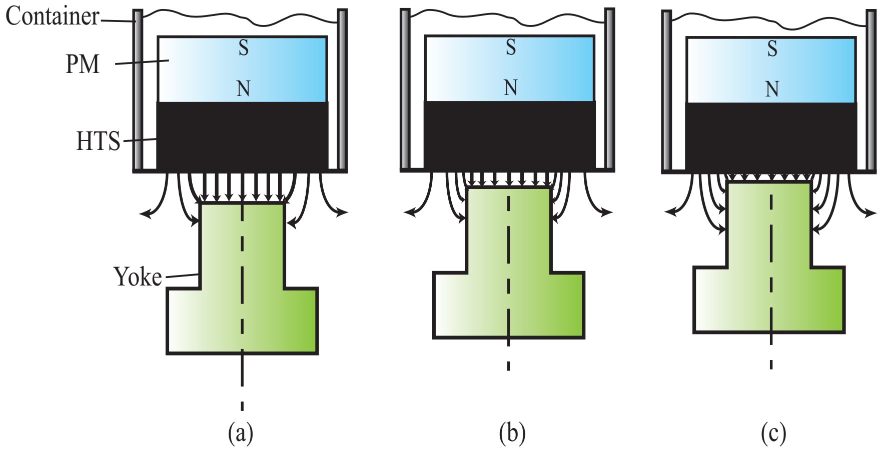

Fig.1. Principle of levitation system

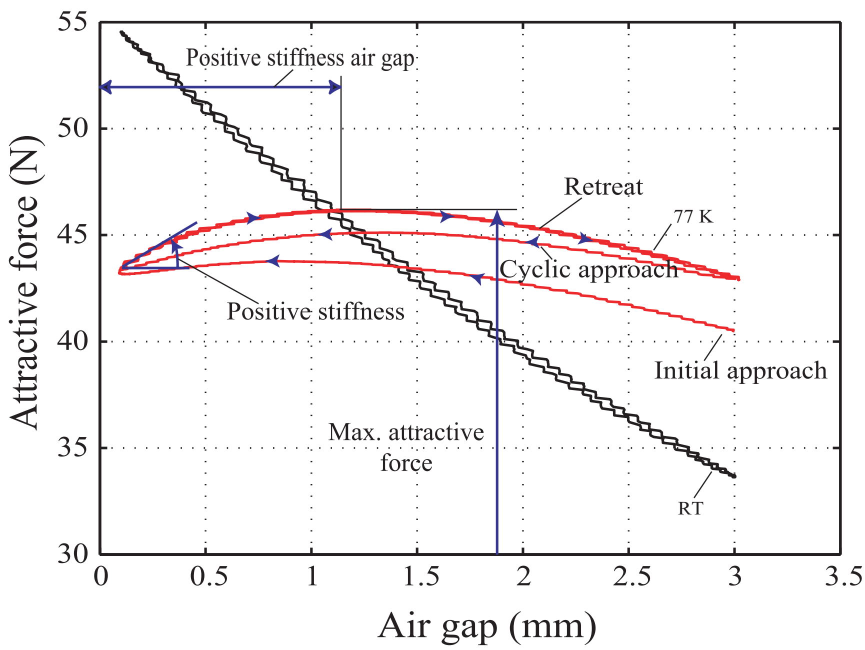

Fig.2. The relationship between attractive force and air gap in room temperature (RT, 300 K) and 77 K, D=15 mm

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 passing 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 low-carbon steel. For instance, the relationships between the attractive force and the gap at 77K and room temperature (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. For the initial approach, the valve of force is lower that next approaches. In the next approaches/ retreats, the paths are unique and different from initial approach path. 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. To image the performance of the system more easily, three parameters are defined as "fundamental parameters" in Fig. 2. In the curve of attractive force vs. gap the finite variation of force over finite variation of displacement in each point is called stiffness. The average of stiffness values throughout the "positive stiffness air gap'' (*PSG*) is presented as stiffness value in this research. Moreover, the range of air gap which system's stiffness is positive is called "positive stiffness air gap" and the maximum value of attractive force is called "max. attractive force".

The main goal of chapter 5 is finding out the principle of the levitation system. On the way towards this goal, three experiments must be undergone. It seems that, when a ferromagnetic yoke is approached to the surface of HTS, the motion of flux (flux creep) causes force reduction. It means that, the positive stiffness is internal phenomenon of HTS. In the first experiment, I cover the surface of the HTS by steel plate to show that the flux creep is not the reason of positive stiffness. Secondly, this question crossed my mind that why low-carbon steel can not be levitated by a permanent magnet, while it can be by a field-cooled (FC) HTS. Then, in this experiment it is found that by approaching the yoke to the surface of PM, the magnetic flux density will increase, however, the magnetic flux density of FC-HTS will not increase by approaching the yoke to FC-HTS. In the last experiment the variation of magnetic flux passing through the HTS and approach yoke is measured by search coil. This experiment shows that trapped flux in the FC-HTS is approximately constant, where, the flux passing through the yoke decreases in the small gap. Consequently, it is shown that because of the "pinning effect" the flux approximately remains constant in the HTS samples and reduction of flux passing through the yoke causes attractive force reduction and positive stiffness.

Passive levitation of a ferromagnetic material was demonstrated by Tsutsui, Hull and Ohsaki, however, the attractive force and the stiffness of their systems were too small for practical applications. For example, the levitation force in Hull, Ohsaki and Tsutsui's systems is 0.0019 N, 0.062 N and 0.084 N per 1 gram of HTS (YBCO) material. The purpose of chapter 6 is finding the ways to enhance the performance of the levitation system (improve the levitation force and stiffness and positive stiffness gap). Several experiments are performed to find out the effects of trapped flux density, thickness of HTS, yoke shape and initial cooling condition. Briefly it is found that, higher trapped flux density causes higher attractive forces. It is also found that, the trapped flux distribution is the most effective parameter on the stiffness of the system. Low trapped flux density causes higher positive stiffness air gap. Therefore, there is a trade-off between attractive force and positive stiffness. Furthermore, the effect of initial cooling gap and distribution of trapped flux are also investigated and it is highlighted that stronger trapped flux causes wider hysteresis loop. By designing a new magnetic circuit, the levitation force in my system is increased drastically to 2.05 N for per 1 gram of HTS material.

Base on the experimental results of chapter 5, by taking this assumption that trapped flux in the HTS are constant at 77 K, two methods for modeling for "pinning effect" are presented in chapter 7. Firstly, a new numerical method to model the pinning effect by available commercial software is developed. Furthermore, by using a correction coefficient an analytical method to asses the relationship between force and gap is developed. The relationship between the attractive force and the air gap is analytical calculated, numerically analyzed and experimentally measured at both, room temperature (RT) and superconductivity state (77 K). The presented methods can be used to estimate the system's behavior when the cylindrical yoke is replaced by a ring yoke. The results obtained from proposed models, analytical and numerical, show a poor agreement with experimental results and also they can not model the hysteresis phenomenon. However, this fact that pinning effect causes positive stiffness is proven by the proposed models. Furthermore, the enhancement of the stiffness by using ring yoke instead of cylindrical yoke is demonstrated by the presented FEM and modified models. It is found that the stiffness of the system reaches to 5.3 N/mm with the ring yoke, while it is about 3.1 N/mm for the cylindrical yoke. Comparison of system's stiffness between ring and cylindrical yoke highlights the effect of rim area in the yoke. In cylindrical yoke the flux passing through the central part of yoke is constant, whereas, the flux in the rim area decreases in approaching. Since there are two rim areas in the ring yoke, the reduction of flux is bigger than the cylindrical yoke. Therefore, the stiffness of ring yoke is higher than cylindrical yoke.

The magnetic fluxes are trapped in the HTS sample, because of pinning effect. By using this phenomenon, two applications for levitation and one application for actuator are proposed in chapter 8. It is found that, by using close loop circuit and thin HTS sample higher pinned flux and consequently higher force and stiffness are achievable. In the first section of this chapter the levitation of heavy mass (8.6 kg) is demonstrated. Moreover, in the second part of this chapter, the "T-shaped" steel rail is also exploited to make a convey system which is able to move by its weight under 5% rail slop. Since the flux can be trapped (stored) in the bulk HTS sample, it can be used as a source of energy for a cryogenic actuator to keep its position for long time without power consumptions. In last section, I combine the HTS and magnetostrictive bimetal to make a zero-power actuator. The proposed actuator showed the holding range of 12 μm for 3 mm thickness of HTS. Furthermore, the controllability of the actuator over its holding range is proved.

Future plans: Two primary tasks follow the research presented here. First, to use this system in practical applications the same as public ground transportation system, the positive stiffness gap must be increased. This could be in refining the cooling process to achieve the suitable trapped magnetic distribution which is compatible with the shape of yoke. Secondly, improve the presented models to simulate the hysteresis behavior of HTS and asses the behavior of system with higher accuracy.