Magnetic Suspension using High Tc Superconductors and Soft Magnetic Materials and it's Application to a Contact-free Linear Guide

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Abstract: It is found that for small gap lengths, the force-gap characteristic between a superconductor with pinned flux and a soft magnetic material with diameters much smaller than that of the pinned area, is similar to that of a superconductor and a permanent magnet. It is considered that some of the pinned flux is subject to a "gathering effect" in the ferromagnetic material. In this paper, a brief review of the "gathering effect" is described. It is followed by an experiment demonstrating a contact-less levitation of carbon steel bulk and two type of non-contact linear guide.

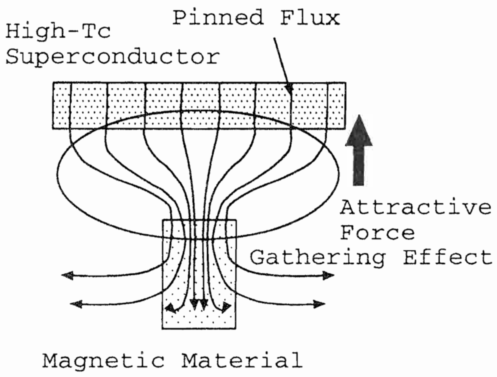
1 Introduction

It is well known that passive suspension, that is, without active control, is possible using a superconductor and a permanent magnet [1]. The explanation for this phenomenon lies in the high Tc superconductor's rejection of a varying magnetic field caused by a spatial displacement of the permanent magnet which generates a stable levitation force[2]. Physically, the reason of levitation of a permanent magnet positioned at the near field of a high Tc superconductor is that the high Tc superconductor pins the magnetic flux of the permanent magnet and counteracts any change in it[3],[4]. The authors have found that the same effect holds if the magnetic field is varied in the presence of a ferromagnetic material whose diameters is much smaller than that of the pinned area. This new fact provides for the possibility of achieving contact-less levitation using steel, and as a result, lead to reduce greatly the system cost. The main contents of this paper are:

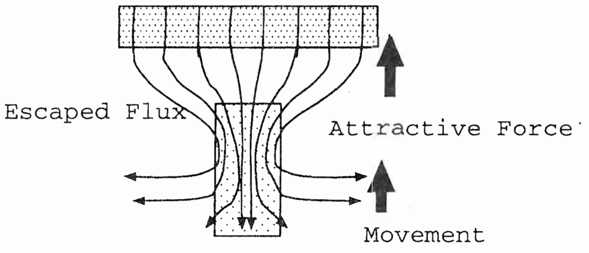
1) Investigation of the restoring force between high-μ soft magnetic materials and flux pinned superconductors;

2). Suspending a steel bulk using High-Tc superconductor with pinned flux;

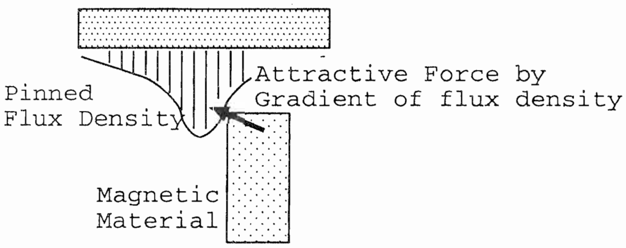
3). Demonstration of the applications of the new levitation technique, two prototype of linear guides.



(a)Flux gathering by magnetic material.



(b)Approach of the magnetic material.



(c)Tangental force by the gradient of the flux density

Fig. 1: Schematic diagram of the flux distribution.

2 Principle of Suspension of Soft Magnetic Material

Figure 1 depicts the pinned flux of a field cooled high Tc superconductor and the interaction with a small diameter soft magnetic cylinder that is approaching the superconductor. As the cylinder approaches the superconductor's near field, the flux lines are increasingly being gathered by the cylinder resulting in an increasing attractive force, as shown in Fig. 1 (a). However, a further air gap reduction causes a decrease in flux passing through the top of the cylinder due to the pinning effect of the superconductor, as shown in Fig. 1 (b). We named this phenomenon "gathering effect". As a direct result, the attractive force decreases as well, implying that a stable suspension of the cylinder in the near field of the superconductor is possible.

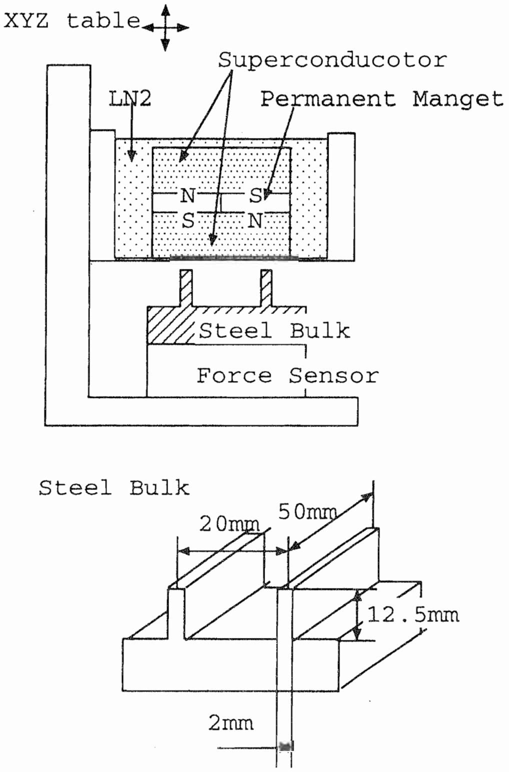


Fig. 2: The schemamtic of the experimental setup

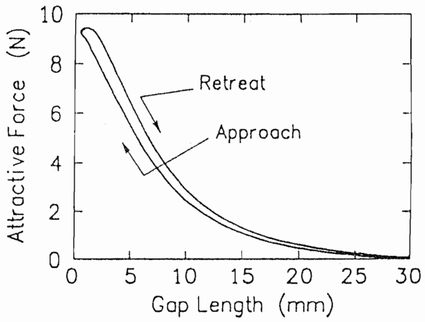
As same as in the vertical direction, the movement of the cylinder in the tangential direction is also stable, due to the gradient of the the flux density. Because the flux density distribution is like shown in Fig. 1(c).

It is noted that the shape of soft magnetic material should be enough smaller than the pinned area, such as thin plate.

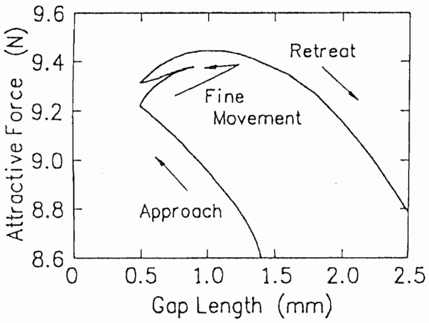
3 Basic Experiment

3.1 Experimental Setup

We have measured the force-gap characteristics of superconductors with pinned flux and steel bulks, using the experimental setup shown in Fig. 2. The LN_2 container is fixed on the XYZ table. Inside it, the superconductors and a permanent magnets which are used to provide pinned magnetic flux are placed. The steel bulk, is fixed on force sensors, which measure the attractive force in the vertical and the tangential force, and are attached under the LN_2 container.



(a) Whole process



(b) Partial magnification

Fig. 3: Attractive force versus gap length curve.

The superconductors are a melt processed YBCO high Tc superconductor, their size is 40×40×12 mm.

For the purpose of providing the magnetic flux for the superconductor, two pairs of magnets are used. One is placed between the superconductors, and other is under it. They are made of Sm-Co magnet material, and have sizes of 40×20×5 mm and 40×20×15 mm respectively.

The soft magnetic material piece is made of carbon steel and has shape shown in Fig. 2.

The experimental procedure is as follows:

1). Placing the superconductors and the inside permanent magnets into the the LN_2 container and the second permanent magnets outside the container.

2). Then, pouring LN_2 into the container. After the Superconductor magnet has been fully cooled, the outside permanent magent placed outside is removed. The left manget is not necessary. But, that is used only to enhance pinned magnetic field.

3) Fix the steel piece on the force sensor, which is placed under the LN_2 container.

4). Moving the superconductor by XYZ stage, and recording the force acting on the soft magnetic piece.

3.2 Experimental Results

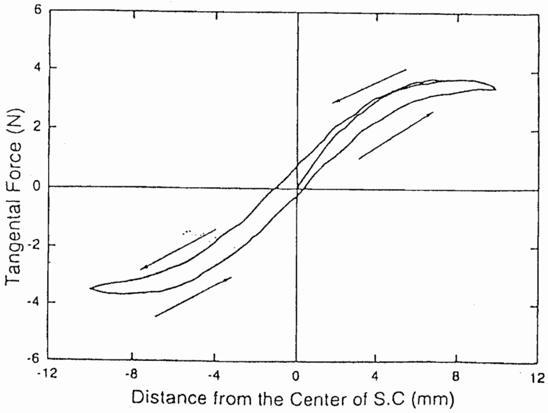


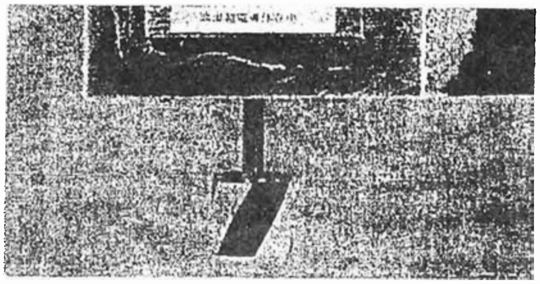
Fig. 4: Tangental force versus tangential distance curve.

Figure 3 is graphs which show the relationship between the gap width and the attractive force. From the graph, it can be observed that the gradient, and consequently the suspension stiffness, is positive for an air gap range of 0.5 mm to 2 mm. Oppositely, while the suspension stiffness is negative for air gap widths exceeding 2 mm. Therefore, stable levitation is only possible for an air gap range of 0.5 mm to 2 mm. Average in the range of 0.5mm to 2mm of the stiffness is 0.4 N/mm and maximum attractive force is 9.4 N. We can also see that the attractive force possesses a hysteresis-like characteristic.

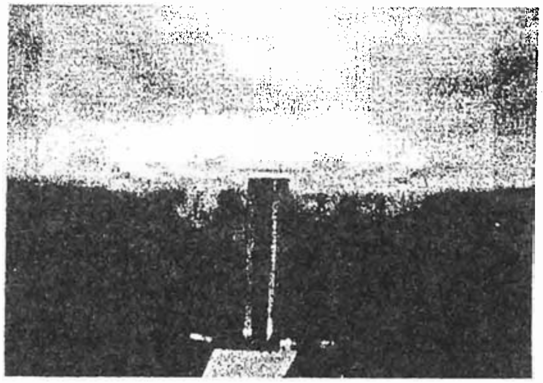
Figure 4 is a graph which shows the relationship between the tangential distance of the steel bulk from the center of the superconductor and the tangential attractive force. The gap between the superconductor and the bulk is kept 0.5 mm. It is noted that the recovery force is appear in which the tangential distance is smaller than 5mm. This is greater than the range of the gap direction. Average of the stiffness is 0.7 N/mm.

4 Levitation of Soft Magnetic Material

Using the principle discussed in section 2, We conducted steel bulks levitation experiments. In our experiments, the diameter of the levitated cylinder is 8 mm and its mass is 180 g. Fig 5 is magnification at the air gap. It is found from Fig. 5 that it took a relatively long time for any intentionally imposed rotation on the cylinder to cease. Any small excursion from the nominal air gap caused by an external disturbance on the cylinder results in an decaying oscillation, indicating a stable system.



(a)



(b)

Fig. 5: Stable, contact-free suspension of a 180g steel weight under a pinned superconductor

5 Linear Guide of Suspension

The importance of the suspension technique mentioned above is that the cost of a linear bearing can be drastically reduced using soft magnetic material instead of permanent magnets[5].

Figure 6 shows a prototype of linear guides using this suspension technique. It is an invented extension of structure in Fig. 1. It uses two parallel rails along the direction of motion. The floater is suspended, without contact, against gravitational forces by the "gathering effect" and is horizontally centered by the gradient of flux density. The floater is moved by gravity, because the rail is slightly inclined.

The cross section of the rail is as same as that describe in section 3. The weight of the floater is 1.4kg. The gap between the floater and the rail is 0.5mm.

6 Linear Guide with Two Tracks

Figure 7 shows another type of linear guide with two tracks. Two tracks similar to that used in one track system are placed on both sides of the floater, with the entire system rotated around its axis by 90 degrees. The gap between the two rails is 32.2 mm.

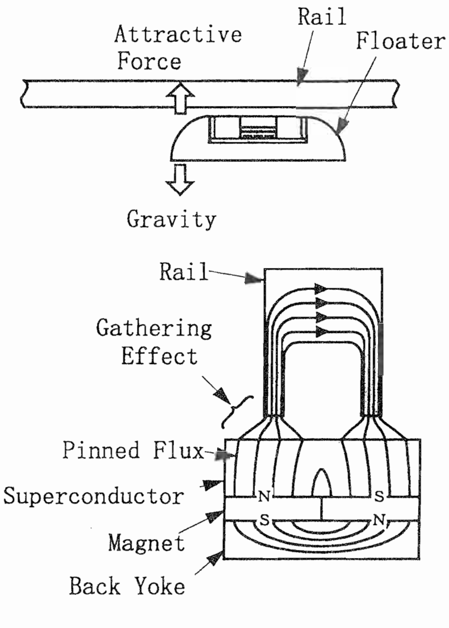


Fig. 6: Linear guide of suspension

The floater has two superconductors and two magnets in the LN_2 case. The width of the floater is 31mm and its weight is 486 g. At the bottom of the floater, a mass is fixed, which is necessary to achieve stable levitation.

The "gathering effect" is used to center the floater and maintain its distance from rails. The gravity force, is balanced against the attractive force by the gradient of flux density.

Because the range of stable levitation using the gradient of flux density is wider than that using gathering effect, the range of the load is wider than single rail model. This means that this model can carry various weight of load.

Figure 8 shows the results of the experiment. The floater was levitated stably between the two rails. The rails were slightly inclined, and the floater moved by gravity feed. Stable levitation are maintained even when the rails were rolled 2 degree. It is also noted that at the equilibrium state, the surface of floater was not parallel to the rails. It is believed that the different flux distribution of the two superconductors caused it.

7 Conclusion

This paper describes a novel phenomenon that the attractive force between a flux-pinned high-Tc superconductor and a soft magnetic bulk having a small diameter or a thin plate is proportional to the air gap width. This

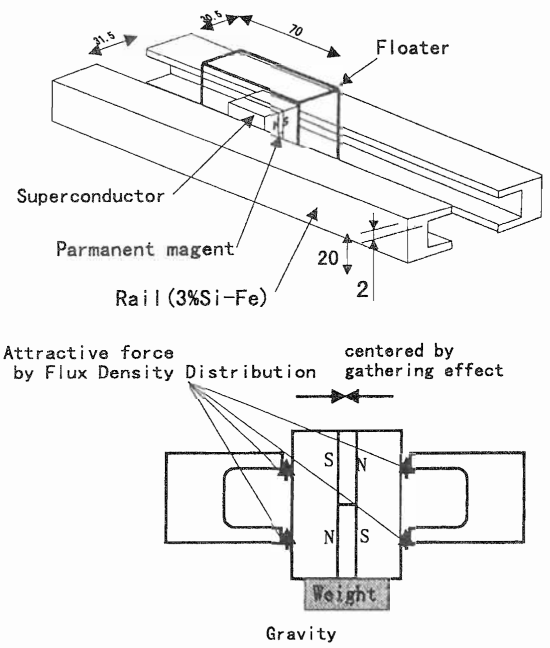
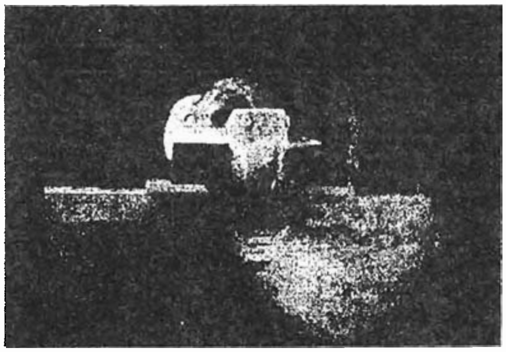
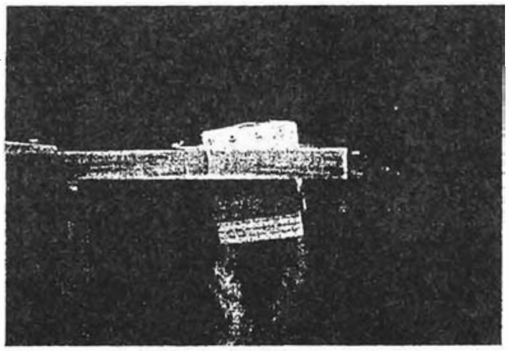


Fig. 7: Linear guide with two tracks



(a) Front view



(b) Side view

Fig. 8: Experiment of the two tracks system

new fact provides the possibility of suspending objects made of soft magnetic materials. Experimental results demonstrating a completely levitation of a carbon steel bulk are shown. In addition, two types of contact-free linear guide systems using the new phenomenon are also presented. The single rail model shows that the suspension of soft magnetic material is suitable to contact-free linear guide. The two rail model shows the improvement on carrying various weight of load.

Traditional magnetic bearings, using high Tc superconductors as the stators and a permanent magnet as the rotor, could not rotate at high speed due to the limited mechanical strength of the magnet. By comparison, a magnetic bearing utilizing the technique mentioned above and having a rotor made of soft magnetic materials, could rotate at very high speed since the soft magnetic materials have higher mechanical strength than permanent magnets. Furthermore, it would be cheaper than the transitional one, owing to the the fact that the soft magnetic materials are cheaper than permanent magnets. So are the case of the linear guides with suspension.

An unfortunate negative characteristics of this method is that stiffness are lower than that of conventional one. The improvement of the suspension stiffness is a future subject of study.

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