# Innovative Magnetic Levitation System by Using Persistent Current in Superconducting Coil

Mochimitsu Komori, Singo Takase, Kaoru Nemoto, Nobuo Sakai, Ken-ichi Asami
Dept. of Applied Science for Integrated System Engineering, Kyushu Institute of Technology
1-1 Sensui, Tobata, Kitakyushu, Fukuoka 804-8550, Japan
E-mail: komori_mk@yahoo.co.jp

***Abstract*---Superconducting technique is applied to the levitation system. Persistent current in superconducting coil and control current in copper coil are used for levitating object and controlling object, respectively. The system is composed of a superconducting coil, a copper coil, a levitated object, a photo sensor, a PD controller, and power amplifiers. In this paper, basic study on superconducting coil and solenoid coil, and the dynamic characteristics of levitated object are performed. This may be the first trial that superconducting coil is used for magnetic levitation.**

## I. Introduction

Magnetic levitation technique is a very promising technology because of no mechanical contact [1], [2]. In general, magnetic levitation technique uses electromagnets (EMs) for controlling the positions of levitated objects. When EMs are applied to levitation systems, much electrical power is necessary for levitating them. Wind channel test equipment with an airplane model is shown in Fig. 1(a). The airplane model (or other models) is supported by a mechanical support to keep it in the center of the wind channel. However, the wind channel needs nothing around the model, because the mechanical support disturbs the environment around the airplane model (or other models). Then, in order not to disturb the environment, magnetic levitation technique is very promising for wind channel test equipments. By using magnetic levitation technology, a wind channel test equipment is proposed as shown in Fig. 1(b). The test equipment is composed of an airplane model, some EMs for levitation and some sensors for detecting model position. In order to get larger distance between EMs and airplane model (levitated object), much larger ampere-turns are necessary. However, in order to get larger ampere-turns, there may be a technical limit for conventional EMs systems.

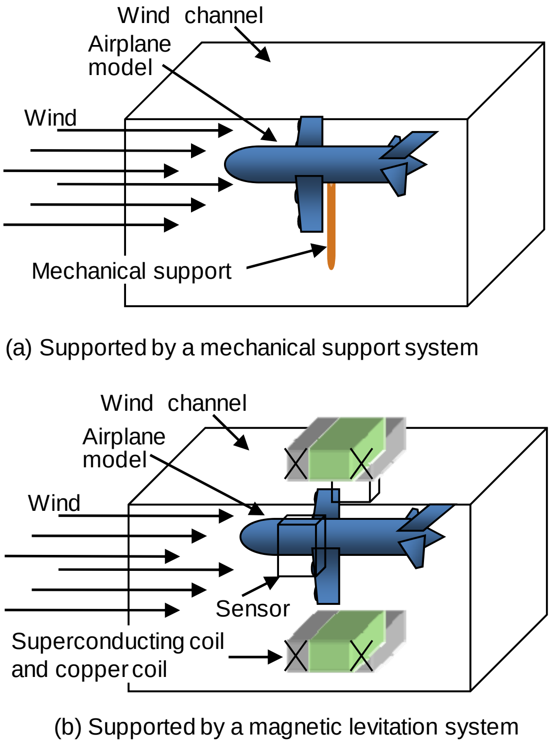


Figure 1. Wind channel test equipment with an airplane supported by (a) a mechanical support system and by (b) a magnetic levitation system

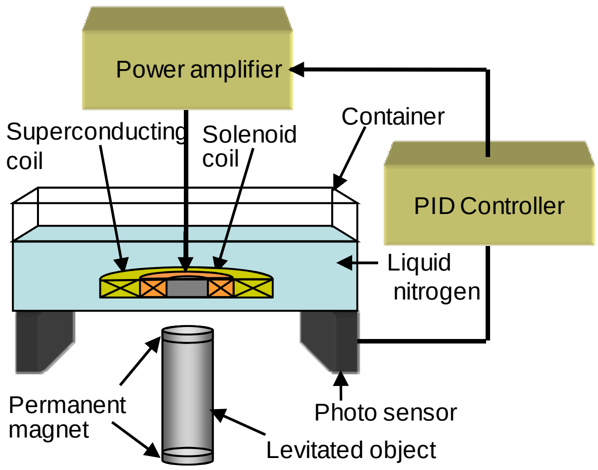


Figure 2. Wind channel test equipment with an object supported by a magnetic levitation system

Table 1 Specifications of supercon-ducting coil

| | Superconducting coil |
|---|---|
| Material | BSCCO |
| Outside diameter | 103.4mm |
| Inside diameter | 60mm |
| Thickness | 10mm |
| Turn | 99.5turn |

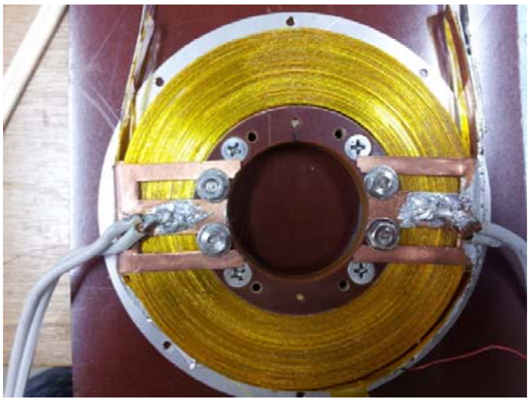

Figure 3. Superconducting coil

Then, in this paper superconducting technique is applied to a levitation system such as a wind channel test equipment [3], [4], [5]. Persistent current in superconducting coil and control current in copper coil are used for levitating object and controlling object, respectively. In this case, there is no electrical power loss in superconducting coil because of no electric resistance of superconducting coil. In this paper, basic studies on superconducting coil and solenoid coil are performed, and dynamic characteristics of levitated object are studied. This may be the first trial that superconducting coils are used for magnetic levitation.

## II. LEVITATION METHOD AND EXPERIMENTAL SETUP

Fig. 2 shows a schematic illustration of a wind channel test equipment with a levitated object supported by a magnetic levitation system. This system is just a levitation system for studying a wind channel test equipment using superconducting technique. The system is composed of a superconducting coil, a copper coil, a levitated object, a photo sensor, a PD controller and a power amplifier. The copper coil ( $\Phi$ 0.3 mm ×500 turns) measures 40 mm in outer diameter, 10 mm in inner diameter and 11 mm in thickness, which is set inside the superconducting coil. Since these coils have no core inside themselves, it is not necessary to worry about core saturation. The superconducting coil and the copper coil are immersed in liquid nitrogen inside the container, and are used for levitating object and controlling object, respectively. Each coil is connected to a power supply, respectively. In the experiment, persistent current is applied to the superconducting coil and control current is applied to the copper coil. The photo sensor is used for detecting the distance of levitated object.

Fig. 3 shows the superconducting coil (BiSCCO) for studying persistent current. Table 1 shows the specifications of the superconducting coil, which measures 103.4 mm in outer diameter, 60 mm in inner diameter and 10 mm in thickness. The maximum permitted current of the superconducting coil is 160 A. In the experiment, a persistent current 11.1 A corresponding to the levitated object weight 68.0 g is applied to the superconducting coil.

Persistent current mode test is performed by using the superconducting coil shown in Fig. 3. In order to make a persistent current, constant current is applied to the superconducting coil by using a DC power supply. After a heater switch is turn ON, the persistent current mode is continued to perform. In the experiment, magnetic flux density on the coil surface corresponding to persistent current is measured. Fig. 4 shows one of the experimental results for persistent current mode test, showing the relationship between magnetic flux density and time. After the heater switch is turned OFF at a time $\approx$ 90 s, the applied current by power supply gradually decreases to zero. Then, the persistent current mode starts at a time $\approx$ 120 s. The persistent current is 20 A, and the persistent current continues for several hundred seconds as shown in Fig. 4. The magnetic flux density decreases to $\cong$ 0.022 T at a time 600 s. This is caused by the energy loss at the solder joint of superconducting coil. If our technique for solder joint is so

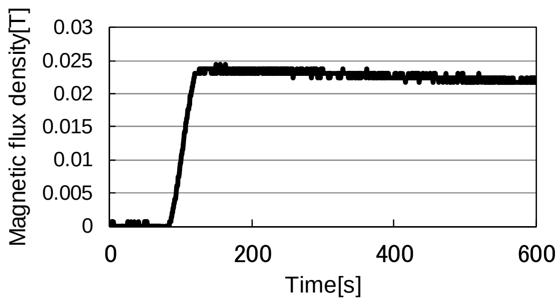


Figure 4. Persistent current mode test, showing the relationship between magnetic flux density and time

satisfactory, the decrease in persistent current will be very small and neglected.

## III. STATIC CHARACTERISTICS

### A. *Attraction force*

Attractive forces between superconducting coil and permanent magnet (PM) are measured. In the experiment, the current from 0 to 20 A is applied to the superconducting coil. Fig. 5 shows the relationship between attractive force and driving current for various distances of 10, 15 and 20 mm. The distance means the gap between superconducting coil surface and PM surface. The figure shows the linear relationships between force and current. The attractive forces at a distance of 20 mm are more than ≅0.7 N. The attractive forces are enough in comparison with the levitated object weight 68.0 g.

Attractive forces between superconducting coil and PM are measured in the distance range of 10 mm – 20 mm. In the experiment, the applied current is kept constant at 20 A. The initial distance is set at 15 mm, then the distance is changed as 10 mm→20 mm→10 mm. The experimental result is shown in Fig. 6. With increasing distance, the attractive force becomes smaller from ≅0.81 N to ≅0.68 N. The change in attractive force is not so large with increasing distance. There is no hysteresis loop in the figure.

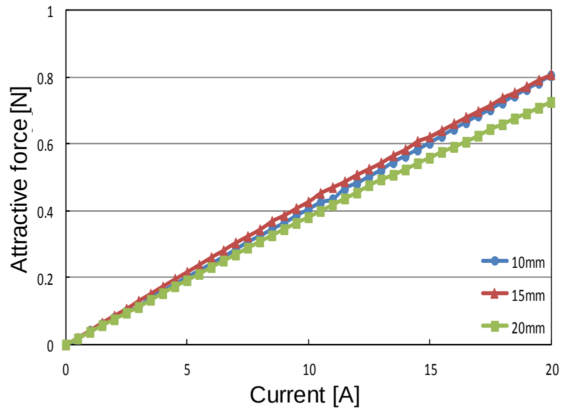


Figure 5. Relationship between attraction force and current

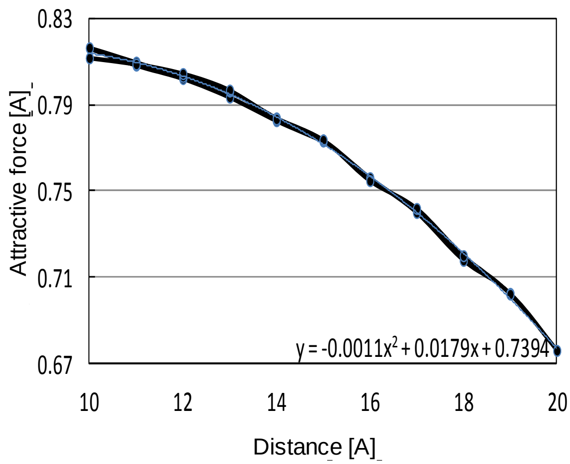


Figure 6. Relationship between attraction force and distance

### B. *Influence between superconducting coil and solenoid coil*

In order to study the influence between superconducting coil and copper coil, magnetic flux densities generated by the superconducting coil and the copper coil are measured. Fig. 7 shows an experimental setup for measuring magnetic flux densities. The experimental setup is composed of the superconducting coil, the copper coil and a Hall sensor. During the experiment, the superconducting coil and copper coil are immersed in liquid nitrogen. The magnetic flux density is measured at a distance 15 mm from the superconducting coil surface by using the Hall sensor (184 mV/T).

Fig. 8 shows the relationship between magnetic flux density and applied current to copper coil. Fig. 8(a) shows the result of magnetic flux density by using copper coil without superconducting coil. The magnetic flux density increases with increasing applied current as shown in Fig. 8(a). The relationship is almost linear over a wide current range. The maximum magnetic flux density at a current 2.0 A is ≅$5.7\times10^{-3}$T. Fig. 8(b) shows the result of magnetic flux density by using copper coil inside the superconducting coil. In the experiment, the superconducting coil is not excited. The magnetic flux density increases with increasing applied current. The relationship is almost linear over a wide current range. The relationship is almost the same as that in Fig. 8(a). The maximum magnetic flux density at a current 2.0 A is ≅$4.9\times10^{-3}$T, which is a little smaller than the flux density ≅$5.7\times10^{-3}$T in Fig. 8(a). This might be caused by the

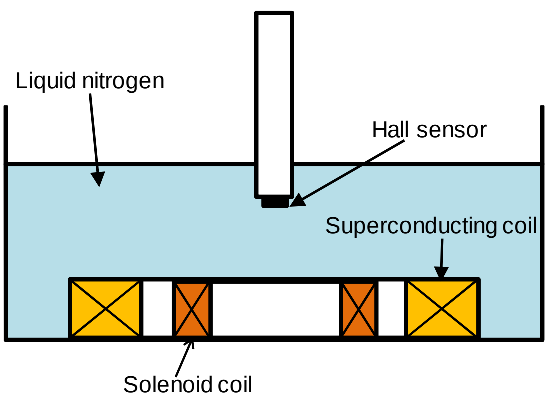


Figure 7. Experimental setup for studying influences between copper coil and superconducting coil

induced current in the superconducting coil, because each end of the superconducting coil is connected.

Fig. 9 shows the relationship between magnetic flux density and applied current to the copper coil. In the experiment, a persistent current 15.2 A (amplifier display: 21 A) is applied to the superconducting coil. The difference between 15.2 A and 21 A is caused by the electric leakage in the driving circuit. The current is applied to the copper coil in the same direction as the persistent current as shown in Fig. 9(a). In the experiment, the applied current is changed from 0 A to 2.0 A. The magnetic flux density increases with increasing applied current as shown in Fig. 9(a). The relationship is almost linear over a wide current range. The minimum and maximum magnetic flux densities at a currents 0 A and 2.0 A are $\cong 16 \times 10^{-3}$ T and $\cong 21 \times 10^{-3}$ T, respectively. Thus, the difference between them is $\cong 5.0 \times 10^{-3}$ T, which is almost equal to the flux density $\cong 4.9 \times 10^{-3}$ T (at a current 2.0 A) in Fig. 8(b). A small hysteresis is observed in Fig. 9(a).

The current is applied to the copper coil in the opposite direction against the persistent current as shown in Fig. 9(b). In the experiment, the applied current is changed from 0 A to 2.0 A. The magnetic flux density decreases with decreasing applied current. The relationship is almost linear over a wide current range. The minimum and maximum magnetic flux densities at a currents 0 A and 2.0 A are $\cong 16 \times 10^{-3}$ T and $\cong 11 \times 10^{-3}$ T, respectively. Thus, the difference between them is $\cong 5.0 \times 10^{-3}$ T, which is almost equal to the flux density $\cong 4.9 \times 10^{-3}$ T (at a current 2.0 A) in Fig. 8(b). A small hysteresis is observed in Fig. 9(b). As a result of these experiments in Figs. 8 and 9, it is found that the superconducting coil a little influences the magnetic flux density by copper coil. However, since the influence is not so large, it is neglected in the experiments hereafter.

### C. *Sensor characteristics*

Fig. 10 shows the experimental setup of distance detecting system by using photo sensor. The system is composed of a photo sensor and a LED light (1.94 W, 3.5 V). Between them a levitated object is set, that is, the object is set just under the superconducting coil center. In the figure, LED light is represented by the red lines and the levitated object disturbs the red light. The photo sensor detects the LED light proportional to the distance of levitated object as shown in Fig. 10. In the experiment, the levitated object is moved upward like a thick arrow as shown in Fig. 10. That is, the LED light on the photo sensor decreases with moving object upward. During the motion upward, the sensor output voltage is measured.

The experimental result is shown in Fig. 11, showing the relationship between sensor output voltage and distance from the container bottom surface. The result shows that the sensor output voltage in the distance range from 8 mm to 12 mm is

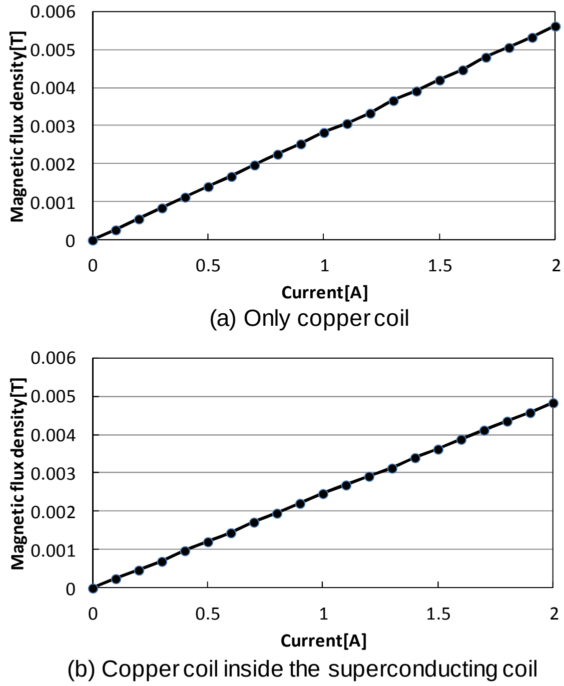


Figure 8 Relationship between magnetic flux density and applied current to copper coil

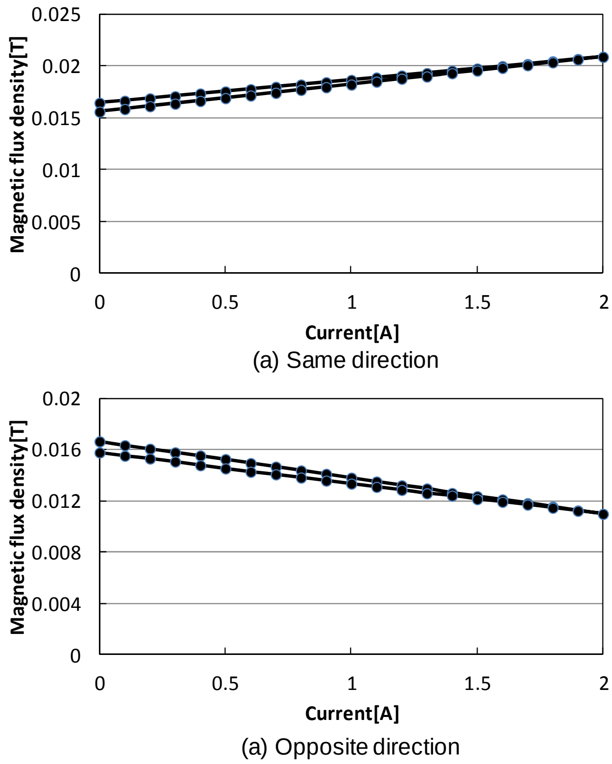


Figure 9. Relationship between magnetic flux density and applied current to copper coil

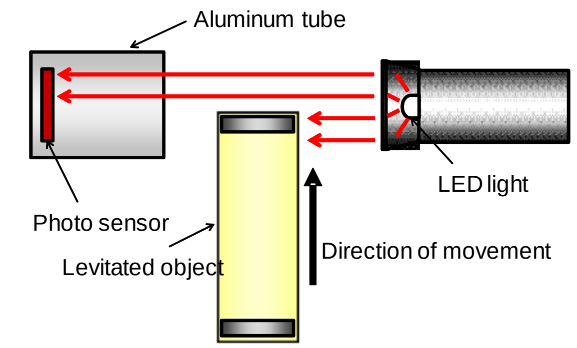


Figure 10. Distance detecting system by using photo sensor

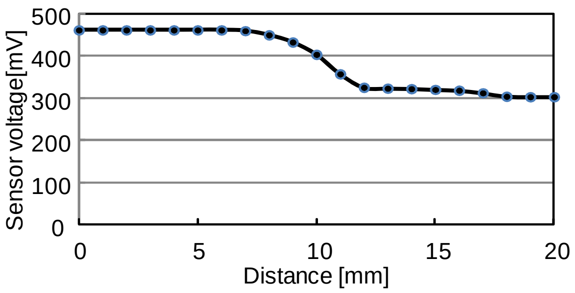


Figure 11. Relationship between sensor output voltage and displacement

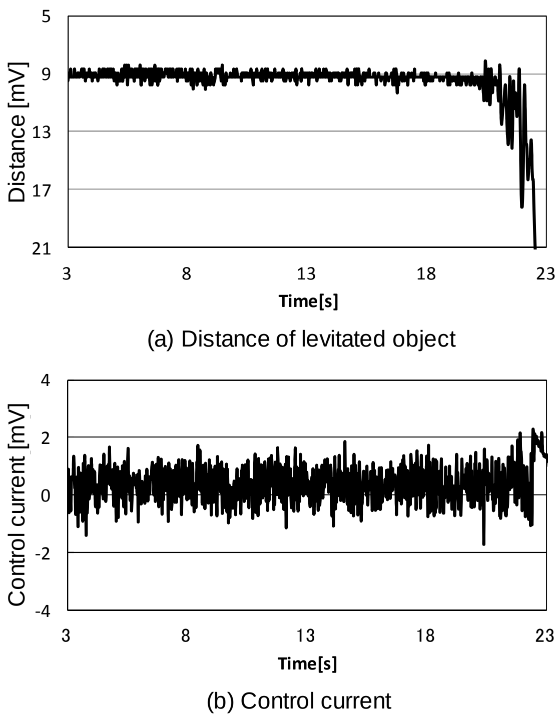


Figure 12. Distance of levitated object and control current

sensitive and useful for sensing the distance. In the experiment hereafter, the distance range from 8 mm to 12 mm is used for the levitation.

## IV. Dynamic Characteristics

A levitated object ( Φ 28.0 ×100 mm, 68.0 g) is made of white plastic, "Duracon". Doughnut-shaped NdFeB PMs are attached to both ends of the levitated object. The PM measures 24 mm (outer diameter) ×8 mm (inner diameter) ×4.5 mm (thickness) in size. The magnetic flux density on the PM surface is 0.209 T. In the experiment, PD control is applied to the levitating system. The experimental result is shown in Fig. 12, representing (a) the distance of levitated object and (b) control current. The levitated object continues to levitate at a distance 9.0 mm for more than ≈15 s as shown in Fig. 12(a). The distance 9.0 mm is the gap between the levitated object top surface and the container bottom surface, which is equal to a distance 15 mm between the levitated object top surface and superconducting coil bottom surface. The displacement amplitude is between -0.5 mm and 0.5 mm, which is not so small. This is because the photo sensor has some noises and the sensor is affected by a lot of frost. For the levitation, the control current applied to the copper coil is shown in Fig. 12(b) and the persistent current is 14.4 A. The levitated object drops at a time ≈20 s as shown in Fig. 12(a). This is because the photo sensor has some noises and the sensor is affected by a lot of frost.

## V. Summary

Superconducting technique is applied to the levitation system. Persistent current in superconducting coil and control current in copper coil are used for levitating object and controlling object, respectively. The basic study on superconducting coil and solenoid coil are performed. It is found that the superconducting coil a little influences the magnetic flux density by copper coil. However, the influence is not so large. The photo sensor output voltage in the distance range from 8 mm to 12 mm is sensitive and useful for sensing the distance. As a result, it is found that the levitated object continues to levitate at a distance 9.0 mm for more than ≈15 s.

Anyway, the object is succeeded to levitate by using the persistent current in the superconducting coil. It may be the first trial that persistent current in superconducting coil is applied to the levitation system.

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