Superconducting Bearings Using High-*Tc* Superconductors for Potential Applications

M. KOMORI AND T. KITAMURA
Department of Mechanical System Engineering
College of Computer Science and System Engineering
Kyusyu Institute of Technology
680-4 Kawazu, Iizuka-City
Fukuoka 820, Japan

ABSTRACT

A non-contact levitation mechanism of high-Tc superconductors is created with the use of alternating-polarity magnets of the same size. It is verified experimentally that the levitation pressure can be optimized with respect to the width of the used magnets. The levitation mechanism is applied to radial bearings with linear motion and rotary motion. The shafts or the rotors of the bearings are supported by the levitation mechanism because of the flux pinning effect. The characteristics of the bearings concerning the repulsion force and other forces were studied. Coupling this levitation mechanism due to the pinning effect and the repulsion force between superconductors and solenoids makes it possible to design a variety of actuators. This study describes the characteristics of the superconducting bearings, such as linear bearings and journal bearings, and the results of experiments for the test. Potential use of these bearings is also discussed.

1. INTRODUCTION

The pinning effect using high-*Tc* superconductor is very promising for stable levitation of superconductors in magnetic field with no contacts or additional control mechanisms [1,2]. After high quality superconductive material was prepared by the Quench-Melt-Growth (QMG) process and the Melt-Powder-Melt-Growth (MPMG) process, many efforts using high-*Tc* superconductor have been made to apply the pinning effect to a variety of levitational systems [3-7]. Among them Moon et al. was the first to apply superconductors to a bearing and study the characteristics [3-6]. Our group has investigated a levitation mechanism using a high-*Tc* superconductor and a set of alternating-polarity magnets [8-11]. The static experiments on the levitation mechanism give larger levitation pressure with increasing alternating-polarity magnets.

By using the levitation mechanism a new superconducting linear actuator has been developed [12]. Fuzzy theory is applied to control the actuator. Conventional control techniques with the use of a kinetic model of the slider in the liquid nitrogen are less practical due to several uncertain factors in its modeling.

2. SUPERCONDUCTING LEVITATION MECHANISM

Two types of superconducting levitation mechanisms are shown in Fig. 1 with magnetic flux lines. Both levitation mechanisms consist of a superconductor and a set of alternating polarity magnets. One type has a magnetization placement perpendicular to the magnet plane as shown in Fig. 1 (a). The other has a magnetization placement parallel to the magnet plane as shown in Fig. 1 (b). In the figures the magnetic flux going out of each *N* pole goes into the adjacent *S* poles to reduce the magnetic energy of the alternating-polarity magnets. Some flux lines are trapped or pinned in the superconductor by the pinning effect and other flux lines are expelled from the superconductor by the Meissner effect. The magnetic flux penetrates easily in the superconductor as long as type-II

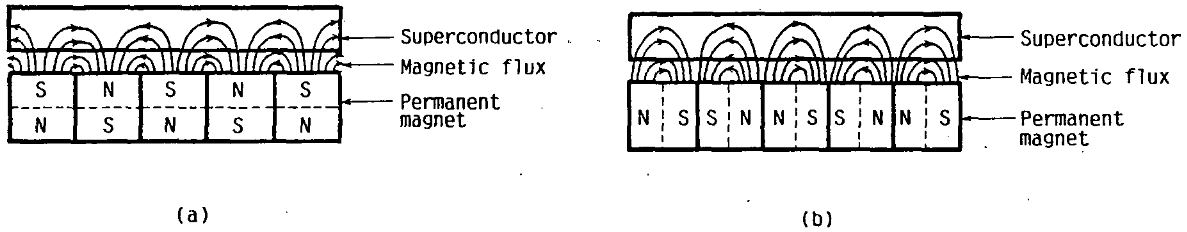

Fig.1 Superconducting levitation mechanism.
(a) Magnetization is perpendicular to the plane.
(b) Magnetization is parallel to the plane.

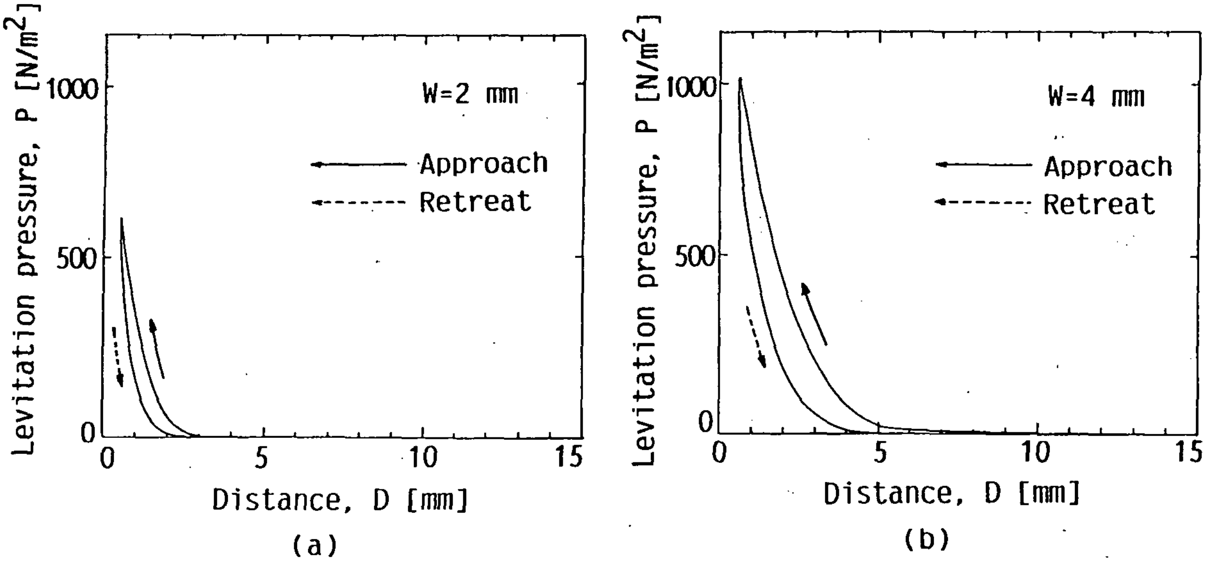

Fig.2 Levitation pressure vs. distance.
(a) Width = 2 mm (b) Width = 4 mm

superconductors such as high-*T*c superconductors are used. The flux pinning effect is much more important than the Meissner effect to the levitation force of the superconductor [3]. The magnetic flux works to support the superconductor like mechanical springs. These two types of the levitation mechanisms are applicable to a variety of mechanisms.

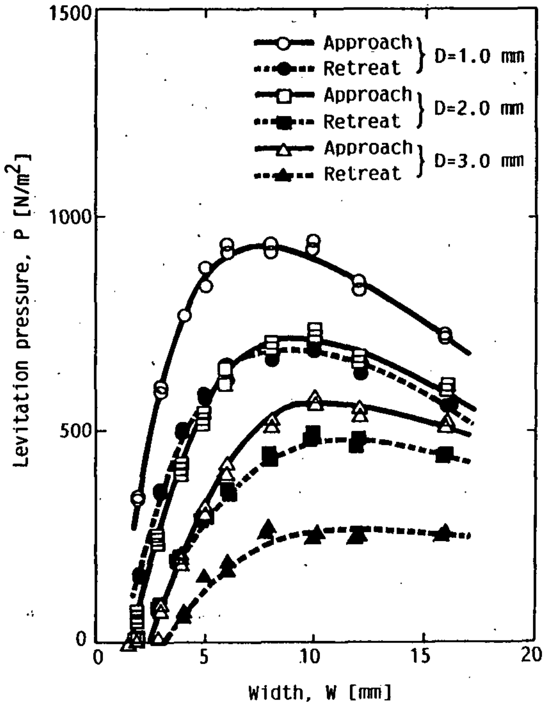

Fig.3 Levitation pressure vs. width of a bar magnet.

Levitation pressures on the superconducting levitation mechanism as shown in Fig. 1 (a) were measured by a beam type load cell containing strain gauges [10]. The levitation pressure is defined as the levitation force measured by the load cell divided by the bottom pole-face area of the magnet assembly. In each experiment the superconductor tile was first warmed to the normal state and then zero-field cooled to the superconducting state. The high-*T*c superconductor used is BiPbSrCaCuO with the critical temperature of $Tc \simeq 100$ K, made by the process of free-sintering method. The magnets are samarium cobalt rare-earth with a residual magnetization of $Br \simeq 1.0$ T. W is the width of a bar magnet.

Figure 2 shows the levitation pressure of the superconductor tile versus distance between the superconductor tile and the magnets. In the experiment the superconductor tile was continuously moved like the arrows in the figure. The result of the widths W=2 and 4 mm is shown in Fig. 2. The hysteresis loops in Fig. 2 (a) and (b) are different from each other. The hysteresis loops are believed to result from the flux pinning effect as already reported by other investigations [3,4]. Choosing the optimal width of a bar magnet providing the largest pressure is important for designing levitation mechanisms.

From the results as shown in Fig. 2, pressure-width relationship is obtained. Figure 3 shows a relationship between the levitation pressure and the width for various distances. From the pressure-width relationship the levitation pressure can be optimized with respect to the magnet width. As another characteristic of the levitation mechanism, it is remarkable that the drag pressure depends on the motion direction in the levitation mechanism [11]. When the superconductor tile moves in the direction perpendicular to magnet placement, the drag pressure is very large. On the other hand, when the superconductor tile moves in the direction parallel to magnet placement, the drag pressure is very small. This is attributed to the flux pinning effect. For designing superconducting actuators including a superconducting bearing using the levitation mechanism with alternating-polarity magnets, it is important to reduce the drag pressure.

3. SUPERCONDUCTING LINEAR BEARING

Radially arranging magnets in the alternating-polarity pattern in a circle gives a superconducting linear bearing as shown in Fig. 4. The magnetic flux lines of the bearing are illustrated in the figure. Some flux lines (solid lines) are expelled from the superconductor shaft and the other flux lines (dotted lines) are trapped in the shaft. These magnetic flux lines between adjacent magnets act as springs to support the superconductor shaft. If the superconductor shaft is moved downwards, the repulsion force acts upward to support the superconductor shaft because of the pinning effect and the Meissner effect. The drag force resists the rotation of the superconductor shaft. But the axial movement of the shaft is free from the drag force.

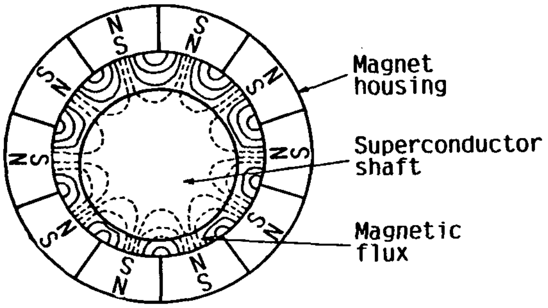

Fig.4 Superconducting radial bearing.

The bearing shown in Fig. 4 is a linear bearing, where the superconductor shaft is supported by all magnets radially attached to the housing. However, using the superconductive technologies gives a new superconducting bearing, where the superconductor shaft is supported by some sets of magnets partially attached to the housing. Our group has made a superconducting linear bearing with a superconductor shaft partially supported. The bearing consists of a superconductor disk-shaped shaft ($YBa_2Cu_3O_x$, 44.5Φ×11.5mm, 99.1 g) supported by two sets of magnet arrangements. A bar magnet of the sets is $4\times5\times40$ mm^3 with $Br \simeq 1.0$ T. The superconductor shaft is prepared by QMG process with a critical current $Jc \simeq 1\times10^4$ A/cm^2 at 1.0 T.

Repulsion force about the linear bearing was measured. The measurements were carried out within the displacement range from -0.5 to 0.5 mm. The origin for the displacement is the center of the magnet housing. The disk-shaped shaft was moved manually by a mechanical stage.

Figure 5 shows the relationship between the repulsion force and the displacement. In Fig 5 (a) the direction of the displacement is perpendicular to the magnet plane. The result shows the hysteresis loops for various displacements. The hysteresis loop becomes small with decreasing displacement. The levitation force of the superconductor shaft acts toward the center of the magnet housing as a restoring force. It is considered not so good that the hysteresis loop exists in the repulsion force. The pinning effect stops the rotary motion of the superconductor disk of the bearing. However there is no friction and drag force in the axial motion of the superconductor disk. These indicate that this mechanism works as a radial bearing with linear motion.

In Fig. 5 (b) the direction of the displacement is parallel to the magnet plane different from that in Fig. 5 (a). The repulsion force is almost equal to that shown in Fig. 5 (a) in spite of the different

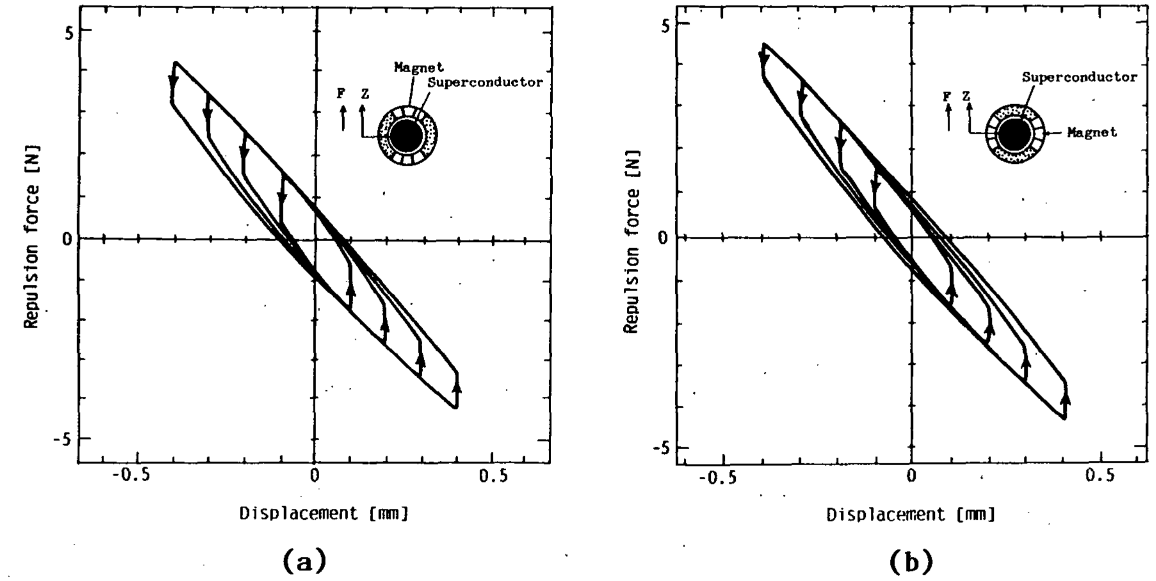

Fig.5 Repulsion force vs. displacement.
(a) The displacement is perpendicular to the magnet plane.
(b) The displacement is parallel to the magnet plane.

directions. From these experiments the repulsion force is almost the same as long as the displacements are in the radial directions. This indicates that two sets of magnet placed in the housing produce enough levitation force to support the superconductor disk. These are attributed to the flux pinning effect.

The restoring torque was measured as shown in Fig. 6. The bearing structure used is the same as that in Fig. 5. θ is an angle which indicates the rotation of the superconductor disk. The result shows hysteresis loops which resemble those shown in Fig. 5. The restoring torque for the rotation angle of 10 degree is about 3×10^{-2} Nm. It is expected that this restoring force becomes larger with increasing thickness of the superconductor disk.

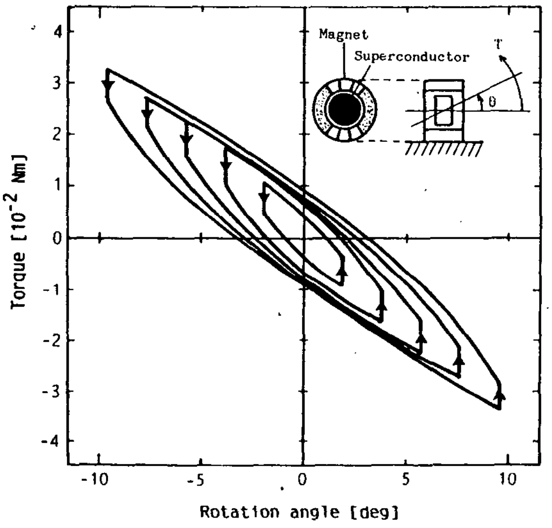

Fig.6 Torque vs. rotation angle.

4. SUPERCONDUCTING JOURNAL BEARING

As another application of the levitation mechanism shown in Fig. 1, a superconducting journal bearing was made. The schematic picture of the journal bearing is shown in Fig. 7. The journal bearing consists of a superconducting housing and a magnet shaft. The superconducting housing is covered with superconductors ($YBa_2Cu_3O_x$, ≃ 1.5 × 3.5× 10 mm^3). The magnet shaft has some ring magnets (OD6Φ ×ID3Φ ×3 mm^3, Br ≃ 1.0 T) whose magnetization is parallel to the axial direction. Figure 8 shows a demonstration of the superconducting journal bearing whose shaft is rotating in the air (superconductors × 12, magnet × 9).

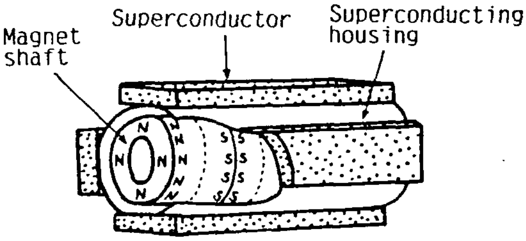

Fig.7 Superconducting journal bearing.

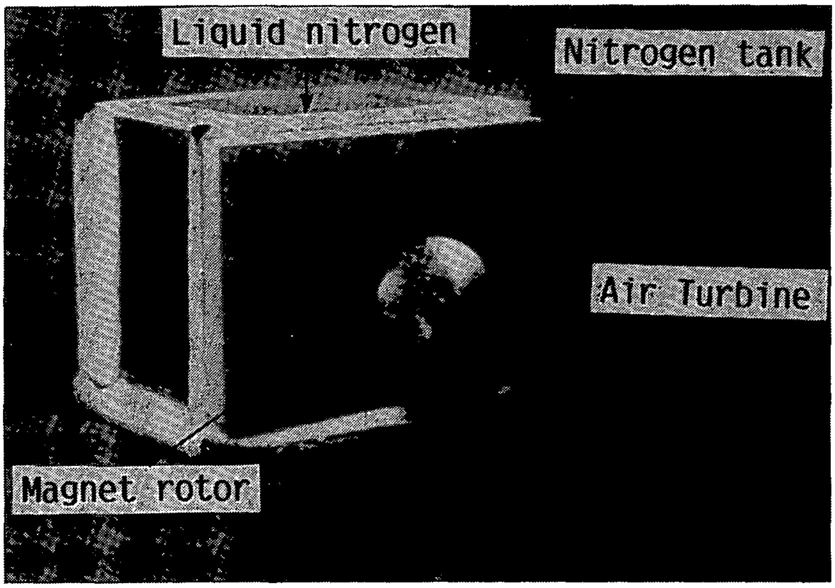

Fig.8 Superconducting journal bearing with the rotating shaft.

The restoring force in the radial direction was measured in the superconducting journal bearing. The superconductors used in the housing was four pieces. The magnet shaft has three ring magnets. Figure 9 shows the relationship between the repulsion force and the displacement. The result shows the hysteresis loops. In the displacement range shown, the repulsion force is linear with respect to the displacement. In the case of eight pieces of the superconductors, the repulsion force is twice as large as that for four pieces. And the repulsion-displacement relationship is also linear in the small displacement

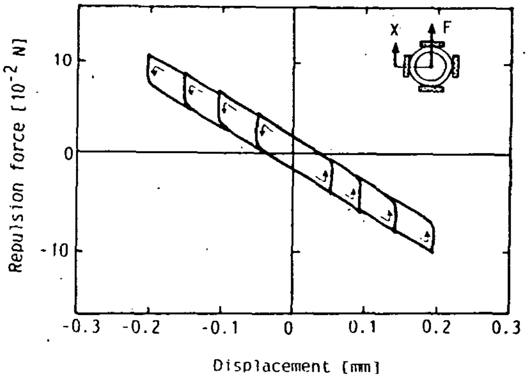

Fig.9 Repulsion force vs. displacement in the radial direction.

range shown in Fig. 9.

The restoring force in the axial direction was measured. The relationship between the repulsion force and the displacement is shown in Fig. 10. The result also shows the hysteresis loops which resemble the relationship shown in Fig. 9. The existence of the repulsion force in the axial direction indicates that this bearing doesn't need a thrust bearing for axial stability. The repulsion force of the magnet shaft is produced by the flux pinning effect.

In order to investigate the rotation characteristics of the new superconducting journal bearing, a rotation test of the bearing by air drive was performed. An air turbine (aluminium, 10 mmΦ ×5 mm, 1.55g) was attached to the bearing with a non-magnetic yoke in the center. The rotation speed was measured using a tachometer. After the air was cut, the speed decay was measured as a function of time. Figure 11 shows the relationship between the rotation speed and the time for various initial rotation speeds. The rotation speed decreases monotonically with increasing time. In each cases the shaft continues rotating for more than 60 sec. Each curve has an exponential decay in the experiment. This shows that a constant drag torque on the rotating shaft due to magnet's asymmetry is negligible. The shaft rotated stably at rotation speeds less than 26000 rpm.

5. APPLICATION TO ACTUATORS

Figure 12 shows a schematic picture of the superconducting linear actuator using the levitation mechanism. The superconducting slider is 2.8 g in weight with two disk-shaped

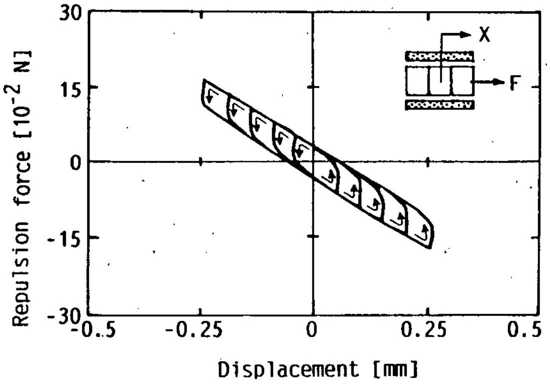

Fig.10 Repulsion force vs.displacement in the axial direction.

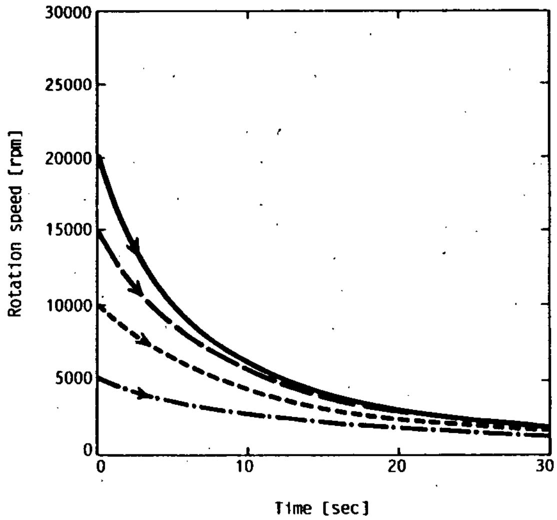

Fig.11 Rotation speed vs. time.

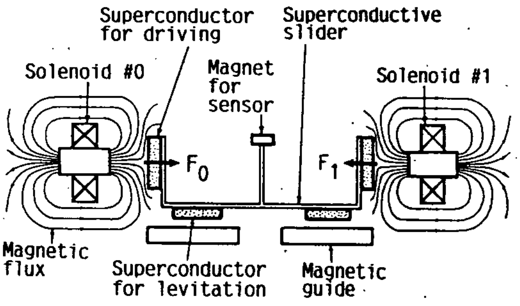

Fig.12 Schematic picture of the linear actuator.

superconductors ($Y_1Ba_2Cu_3O_x$, $7\phi \times 1$ mm) on the base for levitation on each side and 81.7 mm in length. A solenoid (≃500 Turn) is placed facing the superconductor at each end of the slider. The displacement of the slider is detected by a Hall sensor and a magnet ($6 \times 5 \times 3$ mm^3, $Br \simeq 0.4$ T). The magnetic guide includes ten pieces of samarium cobalt bar magnets ($2 \times 20 \times 5$ mm^3, $Br \simeq 1.0$ T) for levitation. The slider is stably levitated at about 1.5 mm height with no mechanical contacts with any side of the guide in liquid nitrogen. The slider is controlled by using fuzzy logic because there exist several difficulties in controlling the superconducting actuator by conventional control techniques for nonlinear inverse relationship and hysteresis relationship between the repulsion force and the position (see Fig.2). The fuzzy controller is composed of linguistic control rules. To simplify the assembler program, membership functions of the fuzzy sets are expressed by the shape of Λ-type with 31 elements and a grade (0∿10) in the staircase.

Figure 13 shows the variable value control result at a frequency of 0.2 Hz for dynamic disturbances. The disturbances are given to the actuator by swinging it in the liquid nitrogen. The angle of +1 degree corresponds to the disturbance of 0.5×10^{-3} N. The error disappears when the disturbances are removed.

Figure 14 shows a schematic picture of a superconducting pump system for extremely low temperature of 4.2 K (liquid helium) or 77 K (nitrogen temperature). This system consists of a superconducting piston, two solenoids to drive the piston, a magnet cylinder for levitation, and a cardiac valve. This system is one of the applications of the linear bearing mentioned in Figs. 4 and 5. This system is being advanced using the superconducting linear bearing and the control technique as previously mentioned.

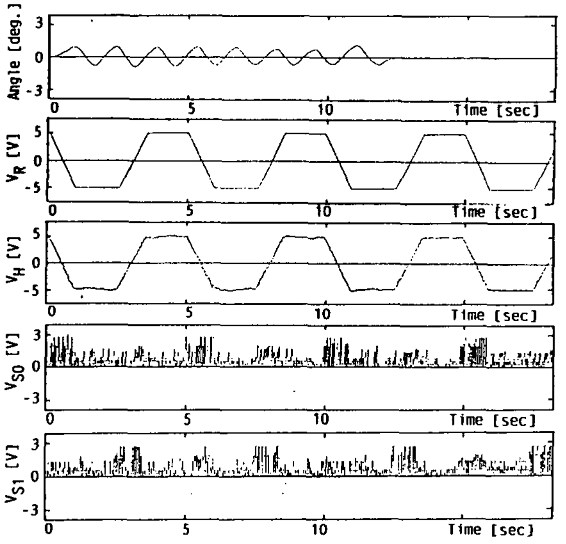

Fig.13 Variable value control result.

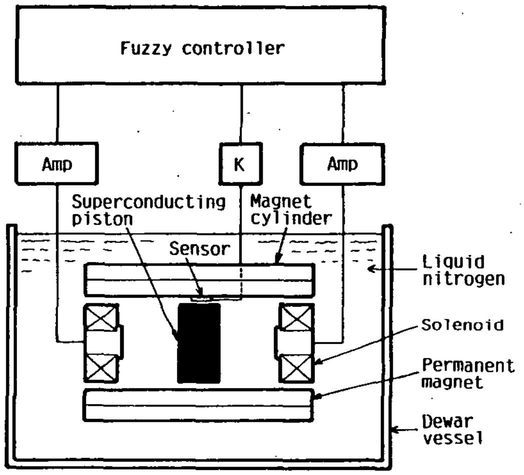

Fig.14 Superconducting pump system.

6. CONCLUSIONS

The characteristics of a non-contact levitation mechanism are studied. The results show that the levitation pressure and the drag pressure depend greatly upon the magnet placement in the mechanism. These characteristics are available for designing a frictionless actuator using the non-contact levitation mechanism.

Using the levitation mechanism the superconducting linear bearing and the superconducting journal bearing were made. The repulsion force of both bearings has hysteresis loops. It is considered that potential use of superconducting bearings is valuable and practical as long as the non-contact levitation mechanism can be applied to the bearings.

Combining the levitation mechanism and a driving force using superocnductors, a new superconducting linear actuator has been developed. Fuzzy control technique is found to be useful for controlling it.

REFERENCES

1. F.Hellman, E.M.Gyorgy, D.W.Johnson,Jr.,H.M.O'Bryan, and R.C.Sherwood, 1988. "Levitation of a magnet over a flat type II superconductor", J.Appl. Phys., 63:447-450.

2. E.H.Brandt,1988."Friction in levitated superconductors",Appl.Phys.Lett. 53:1554-1556.

3. F.C.Moon, M.M.Yanoviak, and R.Ware,1988. "Hysteretic levitation forces in superconducting ceramics", Appl. Phys. Lett. 52:1534-1536.

4. F.C.Moon, K.-C.Weng, and P.-Z.Chang, 1989. "Dynamic magnetic forces in superconducting ceramics", J. Appl. Phys. 66:5643-5645.

5. P.-Z.Chang, F.C.Moon, J.R.Hull, and T.M.Mulcahy, 1990."Levitation force and magnetic stiffness in bulk high-temperature superconductors", J. Appl. Phys. 67:4358-4360.

6. F.C.Moon and P.-Z.Chang,1990: High-speed rotation of magnets on high *Tc* superconducting bearings, Appl.Phys.Lett. 56:397-399.

7. M.Murakami, T.Oyama, H.Fujimoto, T.Taguchi, S.Gotoh, Y.Shiohara, N.Kosizuka, and S.Tanaka,1990. "Large levitation force due to flux pinning in YBaCuO superconductors fabricated by melt-powder-melt-growth process", Jpn.J.Appl.Phys. 29:L1991-L1994.

8. T.Kitamura and M.Komori,1990. "Levitational bearing systems by Meissner effect, Micro System Technology '90, Berlin, pp.826-831.

9. M.Komori and T.Kitamura, 1990. "Development of a superconductive levitational mechanism and its application to a superconductive radial bearing", Cryogenic Engineering, 25:411-413.

10. M.Komori and T.Kitamura, 1991. "Static levitation in a high-*Tc* superconductor tile on magnet arrangements",J.Appl.Phys.,69:7306-7309.

11. M.Komori and T.Kitamura, 1991."Drag pressures of a set of alternating-polarity magnets over a superconductor tile", J.Appl.Phys. 69:2226-2229.

12 M.Komori and T.Kitamura, 1990. "Fuzzy control of a superconductive linear sider", International Coference on Fuzzy Logic & Neural Networks, Iizuka, Japan, pp.87-90.