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# High temperature superconducting levitation flywheel system and its control

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**Abstract**

A simple and stable flywheel system with high temperature superconducting levitation is presented, in which a control is not needed for levitation. In order to have stable levitation, a superconductor and a permanent magnet are used, and three permanent magnets support the top of the shaft. In the part of drive system, eight-poles cylindrical permanent magnet and eight cylindrical coils are used to drive the rotor, in which magnetic forces in the direction perpendicular to the shaft axis are cancelled. Hence, vibration force due to the driving is zero in this system. A coil-type electromagnetic damper is presented which works in the magnetic field of levitation permanent magnet. It consists of four coils. The dampers lie at both ends of the shaft. When the shaft vibrates in the direction perpendicular to the shaft axis, current flows in the damper coil. It generates the electromagnetic force. The force is in proportion to vibration frequencies of the shaft when the velocity feedback is performed, so that the force behaves like damping forces. Using this system, a control like the sensor less control can be performed by using sensors consisting of coils only. Analytical expressions are obtained for the torque for our cylindrical-type motor, and a method for accelerating the shaft is presented by controlling the voltage of the coil based on the expressions. Experimental tests have been carried out. It is clarified that our system has stable levitation, and vibrations are extremely suppressed.


*Keywords:* Levitation; Superconductor; Permanent magnet; Flywheel; Torque; Vibration; Control

## 1. Introduction

Since high temperature superconducting levitation has no contact and no friction, its characteristics have been discussed thoroughly [1–6]. A number of applications have been discussed. The important application is on the non-contact magnetic bearings and energy storage flywheel systems [7–13]. As for an energy storage flywheel, it has a shaft, so that two types of vibrations occur, one is a transnational vibration and the other is pitching vibration. In order to suppress vibrations, two superconductors support both ends of the shaft. The other supporting method is to use large superconductor at the base. For the system, the shaft is also supported by electromagnetic bearings at both ends. A stable levitation is obtained by use of active control of the magnetic bearings [9]. The previous systems usually use induction motor–generator. In the system, since electromagnetic force rotates, the force becomes vibration force. In order to suppress vibrations, an active control is performed to the magnetic bearings. This means that the bearings always consume control energy. Hence, the previous systems are expensive, and always consume energy. The authors presented a levitation system, in which the shaft is supported by a superconductor at the base, and by two permanent magnets at the top [11]. Using the system, the stable levitation was obtained without control. In the system, its rigidity in the direction perpendicular to the shaft axis was still small. In order to decrease electromagnetic force of a motor, we used a special eight-poles motor. However, efficiency was small in comparison with the cylindrical motor. As just mentioned, the previous systems have advantages, but also have disadvantages. In this article, in order to suppress vibrations, we present a new cylindrical-type motor, in which magnetic forces in the direction perpendicular to the axis are cancelled. Then, the driving of the motor causes no vibration force. The system and method of control are presented. The analytical result for accelerating the shaft is obtained, and experimental test verifies the analysis.

## 2. Levitation system

Fig. 1 shows a model of our flywheel system. The lower end is the same as the usual high temperature superconducting levitation system. In the figure, S is a high $T_c$ superconductor that is cooled by liquid nitrogen at 77 K in a cryostat. A ring shaped

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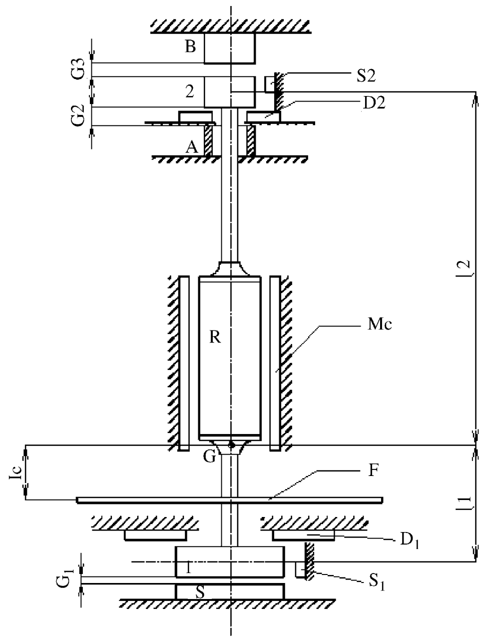


Fig. 1. Geometry of the levitation system: 1, permanent magnet for levitation; 2, permanent magnet for levitation; F, flywheel; A, permanent magnet (fixed); B, permanent magnet (fixed); R, rotor; $M_c$, driving coil; S, superconductor disc; $D_1$, damper coil on the bottom of the shaft; $D_2$, damper coil on the top of the shaft; $S_1$, sensor coil on the bottom of the shaft; $S_2$, sensor coil on the top of the shaft; G, center of gravity.

permanent magnet 1 is connected to a stainless steel shaft in its inner hole. Pinning forces of the superconductor levitate the shaft. In the top have three permanent magnets. Magnets A and B are connected to a frame and magnet 2 with shaft lies between two magnets. N-pole of the magnet faces S-pole for these magnets. Hence, attractive forces act on magnet 2. This means that attractive force in the direction perpendicular to the shaft axis is the restoring force (stable force), but the attractive force in the axial direction is an unstable force. Let $F_{z2}$ be the attractive force between magnet 2 and magnet A, and $F_{z3}$ be the force between magnet 2 and magnet B in the axial direction. When the following relation is satisfied, stable levitation is possible without control:

$$W - k_{z1}Z + F_{z2}(\mathrm{G}_2) - F_{z3}(\mathrm{G}_3) = 0$$

where $W$ is the gravity force of the flywheel and the shaft, $k_{z1}$ the spring constant due to the pinning force of the superconductor and $Z$ is the displacement in the axial direction. The restoring force $k_{z1}Z$ stabilizes the levitation even when there is the axial attractive force due to the permanent magnets in the axial direction.

By adjusting an air gaps between magnet A and magnet 2, and magnet 2 and magnet B, the addition of axial forces at the top of the shaft can be theoretically balanced. In the practical system, it is difficult to make perfect balance, because of the force being unstable attractive forces. In the system, however, the stable restoring force cancels the unbalance force. Hence, we can obtain a stable levitation without control. Especially, when the equations $W + F_{z2}(\mathrm{G}_2) - F_{z3}(\mathrm{G}_3) = 0$ are satisfied, the gravity force of the flywheel and the shaft can be supported by the permanent magnets at the top of the shaft. This equilibrium cannot be satisfied perfectly, of course, but we can obtain the close condition as this. This means that a smaller superconductor is applicable for a heavy flywheel under the help of the attractive force of the permanent magnets. Hence, the flywheel system will be compact, and it requires smaller liquid nitrogen in comparison with the previous systems.

## 3. Motor–generator without exciting forces

### 3.1. Construction of the generator–motor

In the electro energy storage flywheel system, the motor is used as the generator. In the usual motor such as the induction motor, the force due to the electric current of the coil acts in the circumferential direction; this generates the torque, which rotates the shaft. The electric attractive forces in the radial direction are also generated between the coil and the electromagnet due to the magnetic fields of the coil. The force is balanced when there is no vibration. But, when vibrations occur, the force balancing is broken, and an unbalance electrical force rotates. This becomes vibration force when the shaft rotates, because the force is the unstable attractive force, which has no roles of restoring the shaft in the set position. In order to avoid the force, a disc-type motor was proposed, but its efficiency is small in comparison with the cylindrical-type motor (Fig. 2).

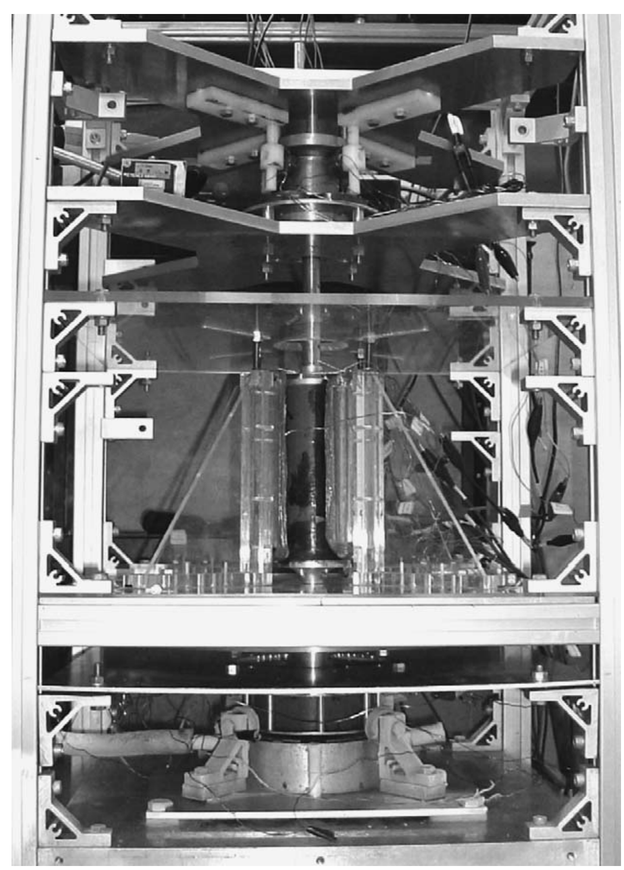

Fig. 2. Picture of the experiment.