

HTS-Magnet Levitation Bearing for Flywheel Energy Storage†

Zule Xia, Ki Ma, Rodger Cooley, and Wei-Kan Chu
Teras Center for Superconductivity, University of Houston,
TX 772044932, U.S.A.

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Advances in high temperature superconducting materials have brought about the possibility of design of totally passive bearings with low friction loss. Bearings with such advantages are useful for kinetic energy storage designs. We have designed and constructed a flywheel prototype using a concept of a hybrid superconducting magnetic bearing (HSMB). The HSMB design uses magnetic forces from permanent magnets for levitation and high temperature superconductors (HTS) in between the magnets for stabilization. The bearings levitate a rotor of 19 kg and the flywheel can currently rotate up to 6,000 RPM. The result from the recent spin-down tests indicates an average frictional energy loss $< 2\%$ per hour. Most of the friction is due to the condition of an imperfect system assembly alignment and an unbalanced rotor. Improvement of the system is ongoing. This paper summarizes our research activity based on some of the results reported recently at several conferences [1,2,3].

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1. Introduction

Superconducting magnetic bearings (SMB) make use of a unique physical interaction between HTS and permanent magnets for levitation, known as 'flux pinning' effect [4]. A commonly used cooling procedure to activate a superconducting bearing, namely the "field-cooled" method, is to cool a HTS in the presence of a magnetic field. Because of the flux-pinning effect, as a HTS is being cooled below the critical temperature, the flux lines are trapped within the HTS, then any attempt for subsequent field change in the vicinity of the superconductor will be resisted [5]. If a proper size of the gap between the magnet and the HTS is arranged, the magnet will be maintained in its position statically as well as dynamically in all directions, by the force and stiffness from the HTS and magnets. Furthermore, if the magnetic field has axial symmetry, a rotor consisting of the magnet can rotate freely about the symmetry axis with almost no energy dissipation. Such superconducting bearings are expected to have a friction loss of $\sim 0.1\%$ of the stored energy per hour [6].

The feasibility of SMB for flywheel energy storage (FES) and other industrial applications has been investigated since the discovery of high temperature superconducting

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materials in the late 80's [7,8,9]. The efforts have been concentrated on building superconducting bearings of industry-scale capability with totally passive levitation and extremely low frictional loss. A promising near-term application of FES using SMB may be for utility industries, since any energy storage systems for utility industries must satisfy the requirements of very high diurnal storage efficiencies ($> 90\%$) for economic reasons [6].

This work presents the initial study of a research program "Flywheel Energy Storage Using Hybrid Superconducting Magnetic bearings". At the Texas Center for Superconductivity at the University of Houston, we have designed and constructed a hybrid superconducting magnetic bearing (HSMB) and built a FES prototype, as shown in Fig. 1, for characterizing the bearing performance. The final goal of the program aims to construct an industrial module of a FES system which is able to maintain 1-2 kWh kinetic energy. The paper will first present the concept behind a HSMB design and then discuss the experimental result.

II. Concept of hybrid superconducting magnetic bearing and rotor-bearing configuration

It has been commonly recognized that the insufficient levitating force from the HTS alone in SMB is one of the main obstacles for practical industry-scale designs. The typical lifting pressure observed is only $70 \sim 140$ kPa as the gap varies from $2 \sim 0$ mm. In this work, we use a hybrid design concept shown in Fig. 2 to achieve a high levitating force. In

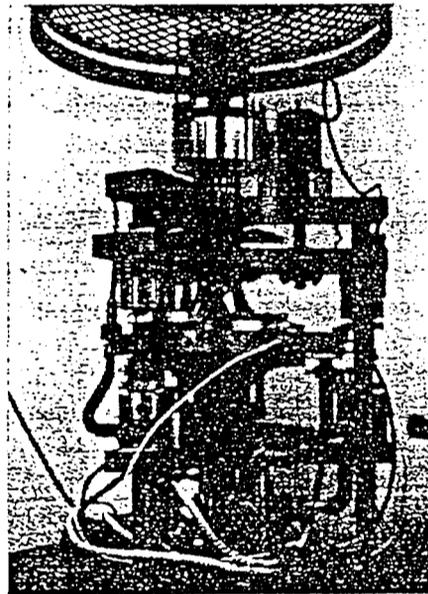


FIG. 1. FES prototype using hybrid superconducting magnetic bearings.

this design, instead of using a direct interaction between a magnet and a HTS for levitating force and stiffness, as the conventional designs shown in Fig. 2, we use magnetic force between the magnets for levitation and a superconductor is placed in between the magnets just for stabilization in both axial and radial directions. Such a configuration, in comparison with the conventional SMB designs, offers much higher levitating force and besides, with the “field-cooled” procedure applied, the system is less susceptible to flux creep because the differences between the external and internal fields are small, due to flux pinning.

The forces and stiffness measured from the top and bottom bearings are listed in Table I. Fig. 3 shows a rotor-bearing levitation configuration. To enhance the overall stiffness, an additional of 10.16 cm (4 inch) outer diameter magnet is attached to the bottom of the rotor: which will interact with a superconducting ring consisting of 12 HTS pellets aligned in a circle.

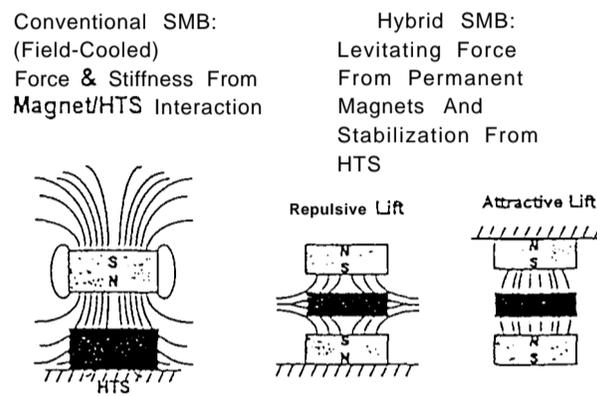


FIG. 2. Configurations of conventional and hybrid SMB designs.

TABLE I. Levitating forces and stiffness for bearing components.

	Top magnet	Top HTS	Bottom magnet	Bottom HTS	12 HTS disks and 4" magnet
Levitating Force(N)	93.1	<1	93.1	<1	
Axial Stiffness (X/mm)	-7.7	10-15	2.2	16-20	30
Radial Stiffness (N/mm)	3.8	2	-1	6~ 8	15

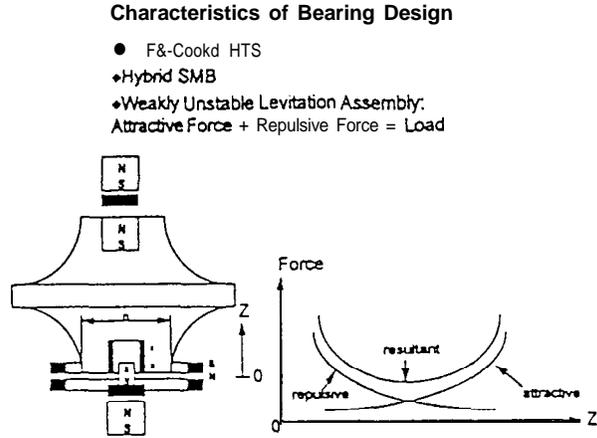


FIG. 3. Rotor-bearing configuration.

To make the inherent instability from magnets to magnets weak enough for HTS to compensate, also shown in Fig. 3, we shared the total weight of the rotor equally between the top and bottom magnets, so that the load can be carried in a marginally unstable position, each bearing providing about 94 Newtons of lifting force.

III. Flywheel spin-down tests and friction loss in bearings

Two rotor spin-down experiments as shown in Fig. 4, one of which runs about 40 hours and another for 15 hours, are conducted in a vacuum of 5×10^{-4} torr and 10^5 torr, respectively. Both are started from the same speed of about 6,000 RPM.

To estimate the friction loss in the bearings, we can calculate the average coefficient of friction and the frictional energy loss per hour by the following formulas [1],

$$\bar{f}_c = \frac{3\pi I}{W_L R \Delta t} (f_1 - f_2) \quad (1)$$

$$\bar{E}_{loss} = \frac{1}{\Delta t} \left[1 - \left(\frac{f_2}{f_1} \right)^2 \right], \quad (2)$$

where

\bar{f}_c = average coefficient of friction;

\bar{E}_{loss} = energy loss per hour as the percentage of the total energy stored;

I = Moment of Inertia ($\text{kg}\cdot\text{m}^2$);

W_L = Load (N);

R = Radius of Flywheel Bottom Surface (m);

Δt = Time interval (hour in (2) and second in (1));

f_1 = Initial Rotating Frequency (Hz);

f_2 = Final Rotating Frequency (Hz);

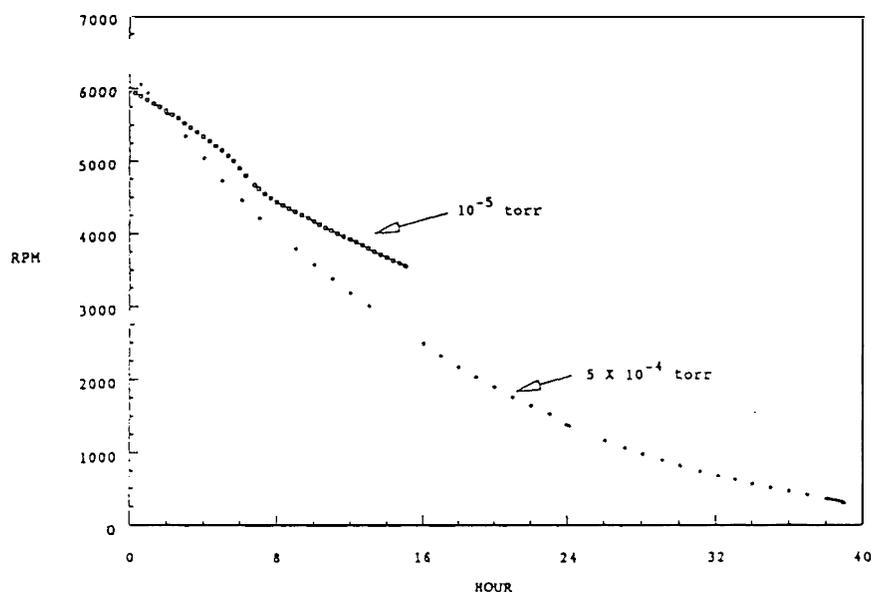


FIG. 4. Rotor spin-down curves.

then the average coefficient of friction under a pressure of 10^{-5} torr by using (1) is

$$\frac{\tau}{f_c} = 0.000193$$

and that spin-down curve indicates an average loss of 4% per hour, compared with the earlier experiment! the 40-hour spin-down test, which exhibits a loss of 5% during the first 15 hours. However the average loss during the whole time span of the 40-hour spin-down comes down to only 2.5% per hour.

To estimate the necessary vacuum level so that the air drag is no longer the dominant loss, we can calculate the power loss due to air drag using the fluid dynamics theory, with the molecular mean free path under a pressure of 10^{-5} torr being $\lambda = 71$ cm, which is larger than a pertinent dimension of the flow field, so that the rotation occurs in free molecular flow. With some empirical constants applied, the power loss (watt) due to air drag can be simplified as[10]

$$P_{cy} = 3.665 \times 10^{-8} p \left(\frac{M}{T} \right)^{0.5} L \omega^2 r^3 (\text{rotor's cylindrical surfaces}) \quad (3a)$$

$$P_{di} = 1.832 \times 10^{-8} p \left(\frac{M}{T} \right)^{0.5} \omega^2 r^4 (\text{rotor's disk surfaces}), \quad (3b)$$

where

p = pressure (torr);

T = temperature (K);

L = surface length (cm);

ω = rotating speed (rad/sec);

r = radius (cm);

M = molecular weight ($M_{air} = 28.97$).

Using (3a) and (3b), we can predict the power loss of air drag by dividing the rotor geometry into disk and cylindrical surfaces. From Table II, which compares the air drag loss predicted by the theory with the average loss from the measurements, we find that: first, although the loss from the measurements is much higher than that predicted by the theory, the difference of the average loss from the two measurements agrees well with the theory and secondly, for the current design, the air drag will be a minor factor in the total loss as the vacuum level is higher than 10^{-5} torr.

The total friction-related energy-loss in the flywheel rotation may be expressed as:

$$E_{loss} = E_{mag} + E_{air}, \quad (4)$$

where E_{air} represents the loss by the residual air drag inside the vacuum chamber, which will slow down the rotation more or less according to the molecular density of the residual gas. Based on the analysis above, we believe that the main contributions to the friction loss is from eddy current and hysteresis effects induced by the offset of magnetic fields from the axial symmetry. The axial asymmetry detected by the position sensors when the flywheel is levitated may result from: (1), a mis-alignment of the magnets caused by poor mechanical assembly tolerance; (2), the non-uniformity of the magnets or (3), static inertial imbalance on the rotor which will produce an unbalanced force in rotation. All of these cause the flywheel to be tilted as well as laterally shifted away from the system geometric axis even when the levitated flywheel is at rest. The eddy current and hysteresis loss then could happen in superconductors as well as in conducting materials which are located in the vicinity of the magnetic field. Hysteresis effects in superconductors have been studied by Hull [6], by changing the geometry between the magnet and the HTS. Since our current cryostats are made of stainless steel, we can expect considerable energy loss in the top surfaces of the cryostats.

IV. Summary and future work

We have designed a hybrid superconducting bearing and tested its performance by

TABLE II. Power loss of air drag predicted by theory and average total loss measured from experiments.

	10^{-5} torr	5×10^{-4} torr	A P
P_{theory}	0.0016 W(6,000 RPM)	0.08 W(6,000 RPM)	0.078 W
$P_{measure}$	0.285 W(average)	0.356 W(average)	0.071 W

constructing a flywheel prototype. This hybrid design has high specific load capacity, compared with HTS bearings which use HTS for levitation. The flywheel of 19 kg (42 lb.) implemented with the HSMB can rotate up to 6,000 RPM. Our rotor spin-down tests show that the frictional energy loss, with the current system parameters, can be < 2% per hour. Our experiments also indicate that the dominant factor for further energy loss reduction is to reduce the eddy current and magnetic hysteresis losses. Our future work includes: re-design of cryostats; improvement of the system alignment; re-design of clutch mechanism; rotor balance and also a study on the system dynamics.

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