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Low Rotational Drag In High-Temperature Superconducting Bearings

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***Abstract*— Bearings consisting of permanent magnets stably levitated over high-temperature superconductors exhibit low rotational drag and have the potential to enable high-efficiency flywheel energy storage. The coefficient of friction μ for such storage systems is derived as a function of bearing parameters and is shown to be an appropriate figure of merit to describe bearing losses. Analysis shows that values of $\mu < 10^{-6}$ enable flywheel standby losses < 0.1 %/hr for high-speed flywheels. A vacuum-chamber experimental apparatus has been constructed to measure values of μ for various experimental bearing designs. Experimental values for μ at low velocity have been as low as 3×10^{-7} for a 89-mm-diameter ring permanent magnet stably levitated over an array of melt-textured Y-Ba-Cu-O. An important loss mechanism occurs from eddy currents induced in the rotating magnet due to the discrete nature of the superconductor array.**

I. INTRODUCTION

A number of researchers have investigated the use of high-temperature superconductors (HTSs) in passive magnetic bearings [1]-[13]. The development of HTS bearings with low rotational loss [14] led to the realization that flywheel energy storage (FES) incorporating HTS bearings with idle losses < 0.1%/h has the potential for very high (>90%) diurnal storage efficiencies. By incorporating HTS bearings with inertial rims made from high-strength composite materials into ultra-high-speed flywheels and combining these with new-technology motor/generators, energy can be stored and released with very low loss [15]. Such high efficiencies cannot be achieved by FES that uses existing bearing technologies, including active magnetic bearings.

High efficiency FES is greatly desired by electric utilities [15]. Without the capacity to store energy, electric utilities are forced to cycle base-load power plants to meet load swings in customer demand. Demand can change by as much as 30% over a 12-h period, resulting in significant costs to utilities as power plant output is adjusted to meet these changes. The transmission system also experiences these changes in load. Thus, an additional advantage of a successful storage technology is the utilization of available nighttime transmission capacity to reduce the need to construct new lines.

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Paramount to the application of HTS bearings to efficient FES is the bearings' ability to achieve low friction at high speed. This paper describes some measurements of losses in experimental HTS bearings and discusses the loss mechanisms.

II. COEFFICIENT OF FRICTION

The figure of merit for the losses associated with a superconducting bearing is the coefficient of friction μ, defined as

$$\mu = F_D/F_L, \tag{1}$$

where F_D is the drag force and F_L is the lift force. The lift force is the weight to be levitated

$$F_L = Mg, \tag{2}$$

where M is the mass and g is the acceleration of gravity. Drag force is calculated from the drag torque

$$\tau_D = F_D R_D = -I\alpha, \tag{3}$$

where R_D is the mean radius at which the drag force acts, I is the total moment of inertia of the rotating object, and α is the angular acceleration,

$$\alpha = 2\pi(df/dt), \tag{4}$$

where f is the frequency of rotation. It is convenient to describe the moment of inertia in terms of the radius of gyration R_γ as follows:

$$I = M R_\gamma^2. \tag{5}$$

We combine Eqs. (1)-(5) to obtain

$$\mu = -(2\pi R_\gamma^2 df/dt)/(gR_D). \tag{6}$$

In Eq. (6), all terms are easily measured or calculated except R_D. There is some ambiguity in its value because, a priori, we do not know the bearing loss mechanism nor how it is distributed over the radius of the bearing. For definiteness, we always take R_D to be the outer radius of the bearing part of the rotor. In our experiments, this corresponds to the outer radius of the levitated permanent magnet.

To determine the value of μ required to achieve the low FES idle loss of 0.1%/hr, we simplify the discussion by

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assuming that all of the mass is located in a rim at radius R ($R_\gamma = R_D = R$). The stored energy E is

$$E = 1/2\ M\ v^2, \quad (7)$$

where $v = 2\pi fR$ is the rim speed. The power loss P is

$$P = F_D\ v = -dE/dt, \quad (8)$$

where t is time. By combining Eqs. (7) and (8), we obtain

$$-(dE/dt)/E = F_D\ v\ /\ (1/2\ M\ v^2), \quad (9)$$

and by using Eqs. (1) and (2)

$$\mu = -[(dE/dt)/E]\ v\ /\ (2\ g). \quad (10)$$

Typically, v is at least 1000 m/s in order to achieve high energy densities for useful energy storage [15], and the desired idle loss is $|dE/dt|/E \leq 0.1\%/h$. This requires that $\mu \leq 1.4 \times 10^{-5}$. This is the maximum coefficient of friction that will give the desired idle losses, if the losses occur at room temperature. However, if HTS bearings are used, an additional factor must be considered because the HTS material must be maintained at cryogenic temperature. Assuming a refrigeration efficiency of ≈30% of the theoretical maximum, ≈14 units of mechanical energy are needed to remove 1 unit of heat at 77 K. Thus, the required value for μ must be reduced by a factor of 14 so that

$$\mu \leq 1.0 \times 10^{-6}.$$

It should be noted that (dE/dt)/E is the desired goal in FES, not μ itself. From Eq. (6) it is apparent that a higher value of μ can be tolerated if $R_\gamma > R_D$. Typically, for a conventional roller bearing, $\mu = 0.001$.

III. EXPERIMENTAL PROCEDURE

We have conducted spin-down tests in a vacuum chamber consisting of a glass belljar chamber evacuated with an oil diffusion pump. This experimental arrangement is illustrated in Fig. 1. The chamber is ≈27 cm in diameter and contains a liquid nitrogen cryogenic chamber within the vacuum. One or more HTS elements is placed inside the liquid nitrogen chamber with the tops of the HTSs against the chamber lid. The vacuum is $<10^{-4}$ Pa when the cryogenic chamber is cold. In one set of experiments the chamber consisted of a cylinder with a 3-mm thick G-10 lid and stainless steel walls and bottom. In another set of experiments, the chamber walls were replaced by G-10.

A rotor consisting of a permanent magnet attached to a mechanical holder is positioned and field cooled. When the HTSs have reached a stable temperature, the positioning device is lowered. At this point the rotor usually sinks about 1 mm and then freely levitates. Spin-up is accomplished by allowing cold nitrogen gas to impinge tangentially on the perimeter of the rotor. The rotation rate is measured with a tachometer, and the flywheel position is determined by a traveling telescope.

To shorten the time required for the experiment, we slow the magnet at intervals by either letting dry nitrogen into the chamber or by introducing mechanical friction against the perimeter of the spinning rotor. To calculate μ for any rotation rate, we fitted a straight line through a series of consecutive data points and used the slope to calculate df/dt. We used this value to calculate μ by using Eq. (6).

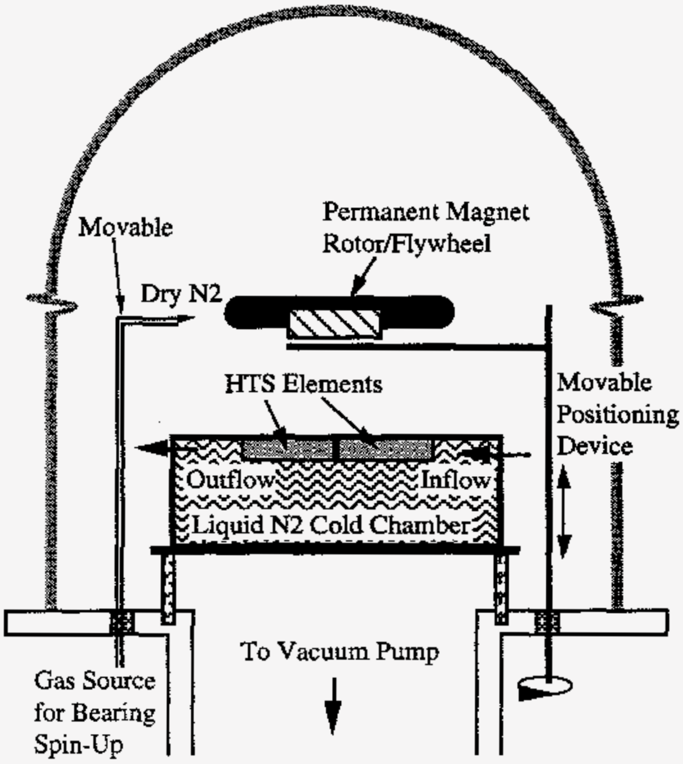

Fig. 1. Schematic representation of belljar spin-down vacuum chamber.

In our spin-down experiments reported here, we have used PM rotors that contain an NdFeB ring that has 89-mm OD, 64-mm ID, and is 13 mm high. The rotor has a mass of 0.32 kg and except for the PM is not electrically conducting. The PM is polarized axially with an internal magnetization of ≈1.2 T. The HTS array in these experiments consisted of HTS cylinders, each ≈18 mm in diameter and 11 mm high. The HTS cylinders were equally spaced around the mean diameter of the PM ring. Each HTS element consisted essentially of a single domain of melt-textured Y-Ba-Cu-O with the c-axis aligned predominantly along the vertical. In one set of experiments an array of 10 HTS cylinders were used. In a second set, 5 HTS cylinders were used.

IV. RESULTS AND DISCUSSION

The rotational-loss mechanisms of HTS bearings are still not well understood, although one of the major mechanisms is associated with inhomogeneities in the magnetic field as a function of azimuthal angle. One important loss from these inhomogeneities is hysteresis loss in the HTS elements. According to the critical-state model of superconductors, the energy loss ΔE per unit area ΔA of superconductor is given by

$$\Delta E/\Delta A = K\,(\Delta B)^3/J_c \qquad (11)$$

where K is a geometry factor, ΔB is the magnetic field inhomogeneity, and J_c is the critical current density of the superconductor. Our experience in using different HTS arrays with the present rotor is that samples with higher J_c have lower μ, which is consistent with Eq. (11). For these purposes, J_c for differing HTS elements may be relatively determined by measuring the levitation force at a fixed height with a standard reference magnet.

In Fig. 2, we show μ as a function of magnet rim velocity for three levitation heights. The results shown in Fig. 2 illustrate several general features of HTS bearing loss with the bearing configuration reported here. To a first approximation, μ is linear with velocity with a non zero intercept. We associate the intercept with the hysteresis loss and the linear dependence with eddy currents in the bearing system. Coefficient μ is smaller when the levitation height is larger. This is understandable from Eq. (11) because ΔB will be smaller at a larger distance from the magnet. The eddy current contribution is also smaller with higher levitation heights for the same reason. The rotor passes through a resonance (at v ≈ 1 m/s). The resonance in μ corresponds to vibrations of the rotor that are visible to the eye. Typically, with all of our experiments, the velocity at which the resonance occurs increases as the levitation height decreases. Because the stiffness of the levitation force behaves similarly, we identify this resonance with the vertical magnetic stiffness. Fortunately, for practical systems, this resonance occurs at very low velocities.

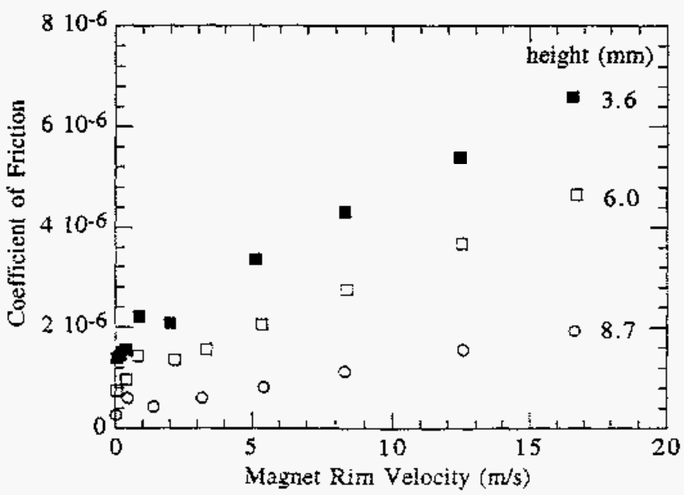

Fig. 2. Coefficient of friction μ as a function of magnet rim velocity with an array of 10 HTS. Height is referenced to top of 3-mm thick G-10 top plate of stainless-steel liquid-nitrogen chamber.

Figure 3 shows results at similar heights when the steel walls of the nitrogen chamber are replaced by G-10. Comparing the results at a similar height between Figs. 2 and 3, we conclude that the steel walls of the nitrogen chamber were responsible for about 30% of the eddy current losses. (In earlier experiments, in which we used a stainless steel lid for the nitrogen chamber, the eddy current losses were even higher.) We also note in comparing Figs. 2 and 3 that the hysteresis loss (zero-velocity μ) is also lower with the G-10 walls, suggesting that some hysteresis loss was occurring in the steel walls.

During the spin-down at a height of 6.6 mm, we conducted several auxiliary tests at a magnet rim velocity of ≈17 m/s to determine the effect of components of the experimental apparatus on the eddy currents. The largest contribution occurred when we brought the copper tube that is used to introduce nitrogen gas during spin-up close to the rotor. This resulted in ≈10% increase in eddy currents. Normally during spin down, the tube is far away from the rotor and contributes negligibly. Doubling the amount of structural steel in the vicinity of the belljar only increased the eddy currents by several percent. We conclude from these experiments that the eddy current losses are either induced in the HTS or in the PM.

At 5.2 mm in Fig. 3, the initial levitation procedure was modified in that the magnet was "jostled" into final position, i.e., a number of transverse and vertical movements of the rotor occurred after the HTSs were superconducting. It is apparent that both the losses are much higher for this procedure. We hypothesize that the jostling induces some horizontal magnetization in the HTSs and that this magnetization remains during spin down and the rotor sees this magnetization as an ac magnetic field. In addition, this suggests that a primary source of eddy current losses is due to the discrete nature of the HTS array. The single domain HTS act as magnetic dipoles, and the PM rotor sees an effective ac magnetic field from the HTSs as it rotates. The eddy currents are induced in the PM itself.

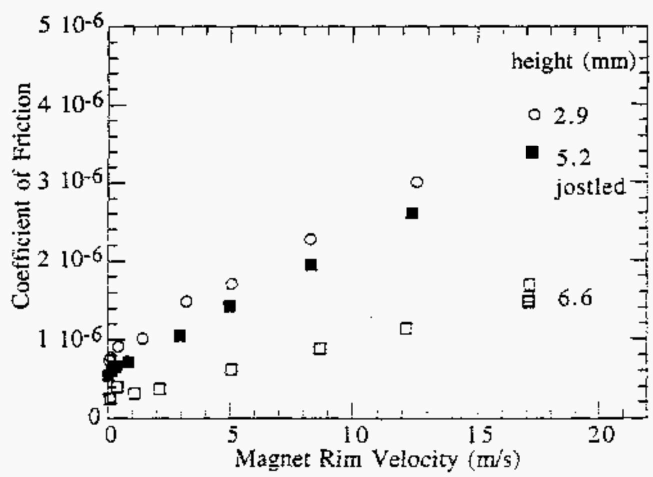

Fig. 3. Coefficient of friction μ as a function of magnet rim velocity with an array of 10 HTS. Height is referenced to top of 4-mm thick G-10 top plate of G-10 liquid-nitrogen chamber.

To further investigate the possibility of eddy current losses in the PM of the rotor, we conducted an experiment in which only 5 HTS cylinders were used and compared it with the results of 10 HTS cylinders at approximately the same levitation height. With only 5 HTS cylinders, the HTS dipoles are further apart and should produce a larger ac magnetic field over the volume of the PM. The results are shown in Fig. 4. As expected, the eddy current losses are much higher with 5 HTS compared with 10 HTS. In addition, the hysteresis losses are also higher. At first, the increase in hysteresis loss is counterintuitive because the inhomogeneity of the magnet did not change and the area of HTS is smaller by a factor of 2. Further relevant observations are that with only 5 HTS the rotor has a smaller vertical magnetic stiffness than with 10 HTS and the vibrations, at least at resonance where they are easily visible by eye, are larger with 5 HTS. Thus, we hypothesize that vertical oscillations contribute to the hysteresis loss.

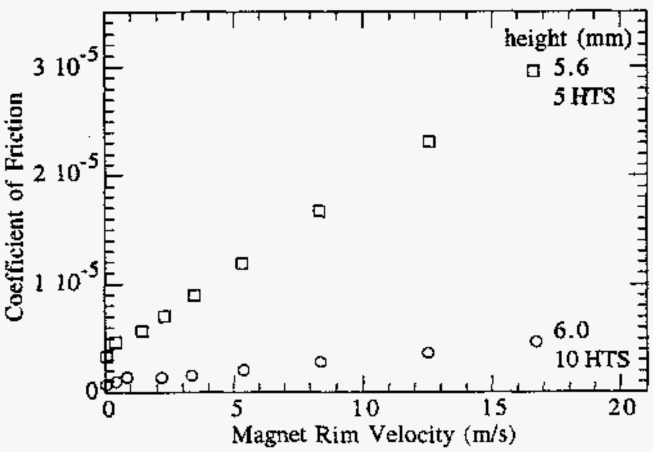

Fig. 4. Coefficient of friction μ as a function of magnet rim velocity with number of HTS as a parameter. Height is referenced to top of 3-mm thick G-10 top plate of stainless steel liquid-nitrogen chamber.

V. CONCLUSIONS

We have obtained a low-speed coefficient of friction of $\mu = 3 \times 10^{-7}$ in a bearing consisting of a 89-mm-diameter ring PM stably levitated over an array of HTS cylinders. Such a low value of μ is of technological interest for use in high-efficiency FES. The low-speed loss is believed due to hysteresis loss in the HTS. Experimental spin-down results indicate that eddy current losses occur in the rotating PM and are caused by the discrete nature of the HTS components.

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