USE OF THIN FILMS IN HIGH-TEMPERATURE SUPERCONDUCTING BEARINGS *

John R. Hull and Ahmet Cansiz
Energy Technology Division, Argonne National Laboratory
9700 South Cass Avenue, Argonne, Illinois 60439

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Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439 USA

Abstract: In a PM/HTS bearing, locating a thin-film HTS above a bulk HTS was expected to maintain the large levitation force provided by the bulk with a lower rotational drag provided by the very high current density of the film. For low drag to be achieved, the thin film must shield the bulk from inhomogeneous magnetic fields. Measurement of rotational drag of a PM/HTS bearing that used a combination of bulk and film HTS showed that the thin film is not effective in reducing the rotational drag. Subsequent experiments, in which an AC coil was placed above the thin-film HTS and the magnetic field on the other side of the film was measured, showed that the thin film provides good shielding when the coil axis is perpendicular to the film surface but poor shielding when the coil axis is parallel to the surface. This is consistent with the lack of reduction in rotational drag being due to a horizontal magnetic moment of the permanent magnet. The poor shielding with the coil axis parallel to the film surface is attributed to the aspect ratio of the film and the three-dimensional nature of the current flow in the film for this coil orientation.

INTRODUCTION

The use of bulk high-temperature superconductors (HTSs) in levitation applications such as magnetic bearings has seen considerable development during the past decade [1]. The most common configuration for a HTS bearing incorporates a rotatable permanent magnet (PM) stably levitated in close proximity to a stationary bulk HTS of (RE)-Ba-Cu-O. More recently, interest in the use of thin-film HTSs in superconducting bearings has increased [2-6]. Although YBCO thin films often have J_c values of >1 MA/cm^2 at 77 K, the thickness of these films is only ≈ 1 μm and they do not provide much levitation force.

The use of high-J_c thin-films in HTS bearings has long been thought to offer the potential for reduced rotational drag [7,8]. This conjecture is based on the generally accepted hysteretic loss mechanism for HTS bearings that is based on the critical-state model. Hysteretic loss is produced whenever there is a cyclic change in applied magnetic field, and the energy loss per cycle is [9]

$$E_h = K\mu_0(\Delta H)^3/J_c \qquad (1)$$

where E_h is the hysteretic energy loss per unit area per cycle, K is a geometric coefficient of order unity, $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is the magnetic permeability of vacuum, $\Delta H = \Delta B/\mu_0$ is the peak-to-peak amplitude of the varying magnetic field, and J_c is the critical current density in the HTS. When a levitated PM spins over a HTS, rotational loss occurs because of azimuthal inhomogeneities of the magnetic field of the PM, which causes a ΔB at a surface location on the HTS over a complete rotation of the PM. The amplitude of the ΔB increases if there is any appreciable whirl amplitude of the PM, in which case the radial gradient of the magnetic field also contributes to the ΔB. One may conceptualize the magnetics of the bearing system as the PM providing a constant magnetic field B that interacts with the HTS to provide levitation force and a circumferentially varying magnetic field ΔB that produces the rotational loss. In general, the ΔB associated with inhomogeneity is much less than the constant magnetic fields B that provide the levitation force.

A further consequence of the critical-state model, beyond the energy loss described in Eq. (1), is that the interior of the HTS is shielded from the varying magnetic field, so that the hysteresis losses occur only on the surface of the HTS. Thus, it was conjectured that if a thin-film HTS were interposed between the PM and bulk HTS, the levitation force would remain approximately the same and most of the hysteretic loss would occur in the thin-film HTS. The thin-film HTS would shield the bulk HTS from the effects of the applied ΔB, so that the bulk HTS experiences only a constant applied magnetic field. Because J_c is so much higher in the thin film, the total hysteretic loss (and therefore the rotational drag on the levitated PM) should be much lower with the HTS film installed.

When the above considerations were tested in rotational drag experiments, we found that the HTS film was not effective in reducing rotational drag [10]. We then conducted magnetic shielding tests on the HTS film to help elucidate its failure to reduce the rotational drag. This article reports the results of the rotational drag and shielding tests. A theoretical interpretation of the results is also provided.

ROTATIONAL DRAG

Experimental Method. A detailed description of the experimental apparatus for rotational drag measurements has been described elsewhere [10,11]. In essence, a PM disk rotor was levitated over a HTS in a vacuum chamber, with an oil-diffusion pump reducing the pressure to <100 μPa. The HTS was inside a room-pressure cryochamber, through which liquid nitrogen flowed from a gravity feed at ≈ 3 kPa. Rotational loss of an HTS bearing is evidenced by the decay rate of the rotational frequency f and is characterized by the coefficient of friction (COF),

$$COF = -[2\pi R_\gamma^2/(gR_D)]\ df/dt \qquad (2)$$

where R_γ is the radius of gyration of the rotor, g is the acceleration of gravity, t is time, and R_D is the weighted mean radius at which the drag force acts.

The height of the levitated PM was measured with a traveling telescope at intervals throughout the experiment, and no change in height from the initial levitation value was observed to within 10 μm. The levitation height in these experiments includes the thickness of the cryochamber (3.5 mm) and the gap between the PM and the top of the cryochamber. The height was recorded after the system had cooled, so as to avoid obfuscation by any changes due to thermal contraction.

Three configurations of HTS were used: (a) bulk HTS, (b) thin-film HTS, and (c) thin-film HTS over bulk HTS.

The bulk HTS was a melt-textured Y-Ba-Cu-O cylinder with its c-axis aligned along the vertical, $J_c = 20$ kA/cm^2, critical temperature $T_c = 92$ K, diameter of 32 mm, and thickness of 22 mm. We chose a thin-film HTS with a diameter significantly larger than that of the bulk HTS, hoping that the film would significantly shield the bulk. The disk-shaped thin-film Y-Ba-Cu-O HTS had $J_c = 3.7$-4.1 MA/cm^2, critical temperature $T_c = 89.2$-89.6 K, diameter of 51 mm, and thickness of 350 nm. The film was deposited on a La-Al-O$_3$ substrate with a thickness of 0.5 mm. When the film was used together with the bulk, they were coaxial and the film substrate was immediately above the bulk.

The same PM rotor was used in all the tests. The PM rotor is an axially polarized NdFeB disk with magnetization of $\mu_0 M \approx 1.1$ T, diameter of 25.4 mm, height of 6.35 mm, and mass of 35.6 gm. The levitation force provided by the thin-film HTS was too low to levitate this PM. The levitational force was augmented by placing a stationary PM above the rotor in an Evershed configuration to produce an attractive force between the two PMs [12]. The distance between the two PMs was adjusted to that the upward force due to magnetic attraction was slightly lower than the gravitational force downward. Because the additional PM in the Evershed configuration does not move, it does not contribute to hysteresis loss in the thin-film HTS. The velocities of the experiment are low enough that loss due to eddy currents induced by relative velocity of the PMs will be negligible compared to the hysteresis loss.
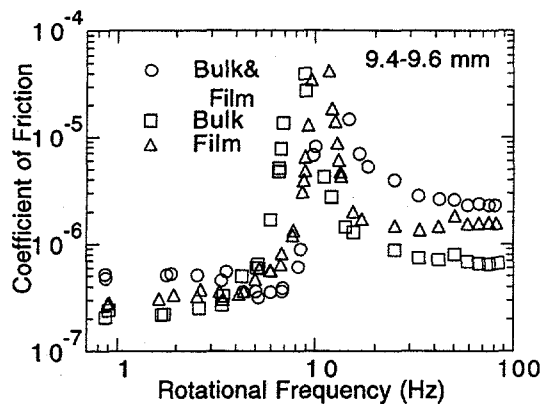
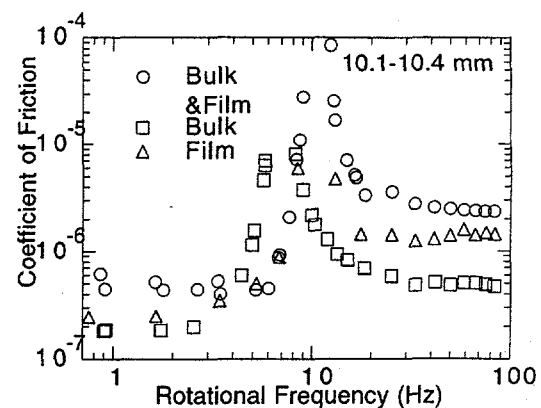**Fig. 1.** COF vs. frequency at 9.4-9.6 mm height for PM levitated over HTS in various HTS configurations.

Fig. 2. COF vs. frequency at 10.1-10.4 mm height for PM levitated over HTS in various HTS configurations.
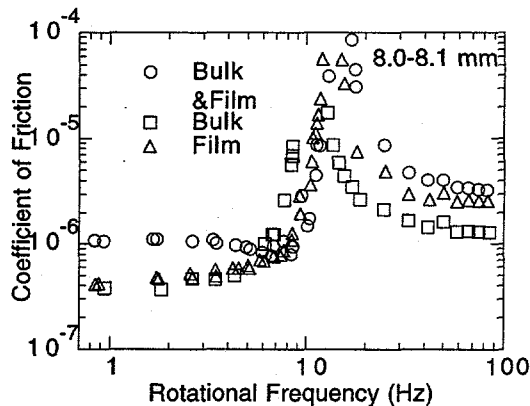

Fig. 3. COF vs. frequency at 8.0-8.1 mm height for PM levitated over HTS in various HTS configurations.

Results. In Figs. 1-3, the data sets are arranged to show the behavior for each HTS configuration at approximately the same levitation height. For all the levitation heights, the resonant frequency is consistently lowest for the bulk alone and highest for the combination of bulk and film. For all the levitation heights, both above and below the resonance, the minimum loss occurred when bulk HTS was used alone, and the loss was maximum when the bulk and film were used together. In these regions, the COF of the bulk and film is approximately equal to the sum of the COFs for the bulk alone and the film alone.

We assumed that the substrate on which the thin film was deposited was not contributing to the rotational loss. An experiment was performed in which a bare substrate (without an HTS film) was placed above the bulk HTS. The rotational loss in this experiment was essentially identical to that of the bulk HTS alone, consistent with our assumption.

SHIELDING

The results of the rotational loss measurements were opposite to our original expectations and motivated the shielding experiments described in this section. Although the mean magnetic moment of the PM is in the vertical direction, any inhomogeneity in the PM is likely to have a substantial amount of its magnetic moment in the horizontal direction. This horizontal moment has been previously ignored in analyzing HTS bearings.

Experimental Method. The same HTS thin film used in the experiments described in the previous section was used as a barrier between two coils. The source coil was wound with 220 turns on a nonconducting parallelepiped former that was 10 mm long, 5 mm wide, and 10 mm high. The pickup coil was wound with 100 turns on a cylindrical former that was 10 mm in diameter and 5 mm high. The coils were oriented coaxially in the vertical direction and constructed to rotate in a single vertical plane. The rotation axis of the source coil was 11 mm above the HTS film, and the rotation axis of the pickup coil was 8.5 mm below the film substrate. The source coil was connected to a function generator that provided a sinusoidal signal of known voltage and frequency. The current through the source coil was measured with a shunt resistor and was found to be proportional to the drive voltage for all of the frequencies used in the experiment.

The voltage in the pickup coil was measured by a lock-in amplifier that was referenced to the function generator. Measurements were taken with the HTS film absent and with the HTS film present and submerged in liquid nitrogen. Frequency f varied from 50 Hz to 3.0 kHz, and the drive voltage V_0 varied from 1.0 V to 5.0 V. At the maximum voltage, the peak amplitude of the current in the source coil was 170 mA, corresponding to a peak magnetic field amplitude of about 420 μT at the surface of the HTS film when the axis of the source coil was oriented perpendicular to the film ($\Phi_s = 0°$).

Results. Figure 4 shows the voltage on the pickup coil when the film is present divided by the voltage with the film absent as a function of frequency for different combinations of source and pickup coil angle. Figure 4 clearly shows that the ratios are independent of frequency. These results were also independent of the coil drive voltage.

For a fixed frequency and drive voltage, Fig. 5 shows the pickup coil voltage as a function of pickup coil angle Φ_p for three orientations of the source coil. When the axis of the source coil is perpendicular to the film surface ($\Phi_s = 0$), the pickup coil voltage is lowest, indicating that the maximum shielding is occurring. Figure 4 indicates that only about 2% of the field penetrates in this orientation. As a function of Φ_p, the voltage exhibits approximately a cosine dependence, which implies that the magnetic field on the shielded side of the film is predominantly vertical.

When the source coil is horizontal ($\Phi_s = 90°$), the pickup voltage is approximately a sine function of Φ_p, indicating that the field on the shielded side is predominantly horizontal. The maximum pickup voltage (at $\Phi_p = 90°$) is about four times higher in this case than the maximum (at $\Phi_p = 0$) for $\Phi_s = 0$, despite the somewhat lower magnetic field at the film surface. This result confirms our hypothesis that the film does not shield horizontal magnetic moments very well. When the source coil is oriented at 45°, the results are a linear mixture of the two extreme cases.
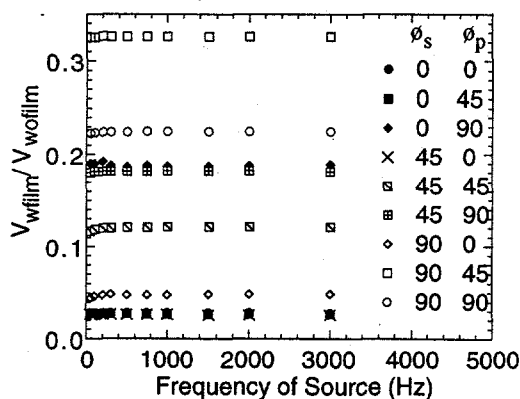

Fig. 4. Pickup coil ratio of voltage with film present divided by voltage without film for different combinations of source coil angle Φ_s and pickup coil angle Φ_p.
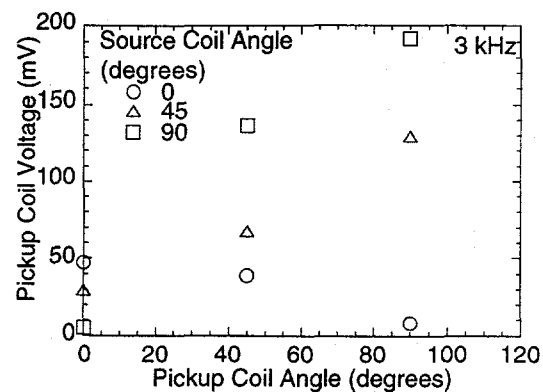
Fig. 5. Pickup coil voltage as a function of pickup coil angle Φ_p for different source coil angles Φ_s. Data from f = 3 kHz, and V_0 = 1.0 V.

The case of a thin disk in a uniform applied magnetic field has undergone considerable analysis [13-15], but the configuration of our experiment is considerably more complicated and seemingly not yet susceptible to elementary analysis. We have shown previously that if drag of magnetic flux through the film were the dominant loss mechanism, the loss in the film should be much higher [12]. We have also shown that the J_c and thickness of the film is sufficient to shield out the expected magnetic field from a vertically oriented magnetic dipole [12]. This result is consistent with the results of the experiments described in this section.

Based on the properties of the PM used in the experiments and assuming Eq. (1) is applicable, one would expect the COF to be lower by at least a factor of 25 with the film, compared to the case of the bulk HTS alone. Because the COF is not lower for the film, plus the COF when bulk and film are used together are essentially the sum of the COFs when they are used separately, we believed that there is probably a nearly complete lack of shielding of the bulk HTS by the film. This hypothesis is verified by the results of the shielding experiments.
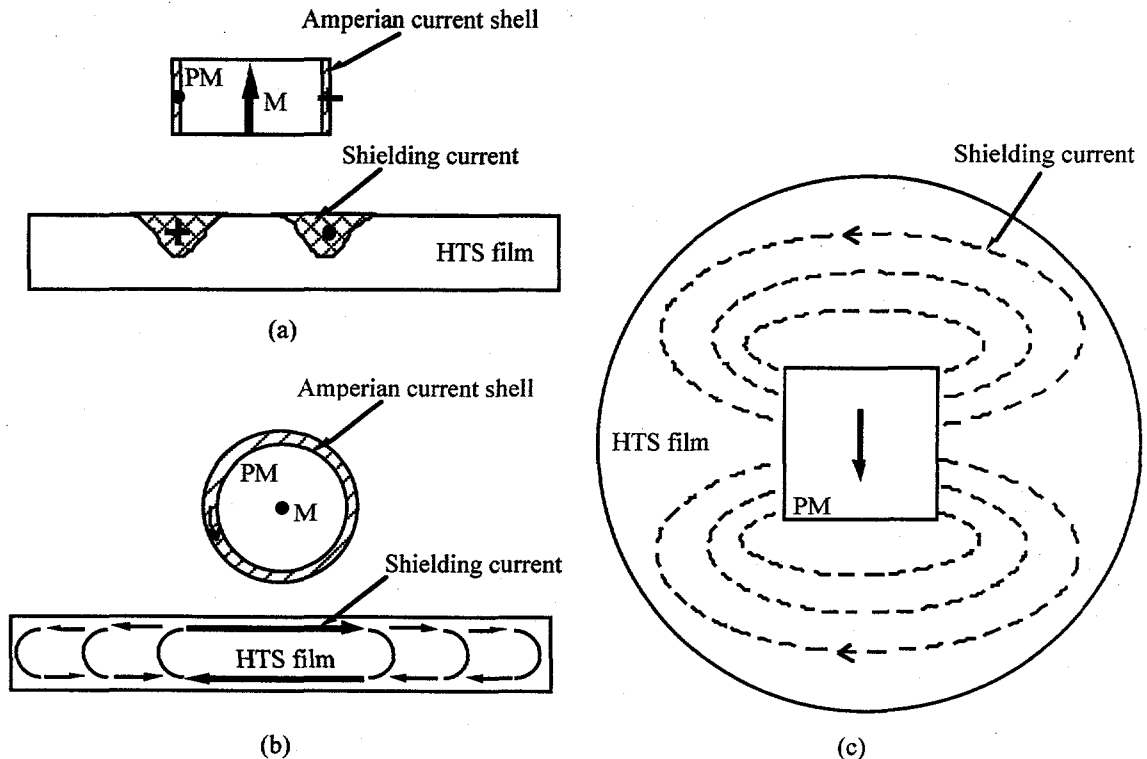

Fig. 6. Schematic of hypothesized current flow in HTS film. (a) Vertical cross section, where magnetization of PM is perpendicular to surface of film. (b) Vertical cross section, where magnetization of PM is in plane of film and current flows through film thickness. (c) Top view, where magnetization of PM is in plane of film and current flows in plane of film.

These results lead us to consider the three-dimensional nature of the currents in the film. The currents under consideration are those caused by the PM inhomogeneity and are in general different from the currents associated with the levitation. The main possibilities are shown in Fig. 6. If a magnetic dipole were oriented perpendicular to the film surface, as indicated in Fig. 6(a), currents need run only in the plane of the film and mainly in the region immediately below the perimeter of the PM, and we should be able to shield the field out of the film interior and below the film, which is consistent with the experimental results. However, if the dipole moment is oriented parallel to the film surface, as indicated in Figs. 6(b) and 6(c), then there are two major possible current flows. To shield the applied field in this orientation, currents at the surface of the film must flow in the same direction as the fictitious Amperian currents in the bottom arc of the PM, as indicated in Figs. 6(b) and 6(c). Because current is conserved in these systems, the currents must return within the system, either by flowing through the thickness of the film and passing along the bottom half in the opposite direction, as shown in Fig. 6(b), or in the plane of

the film around the perimeter of the inhomogeneity, as shown in Fig. 6(c). In either case, the extended area over which the current must flow (compared to that shown in Fig. 6(a)), is probably sufficient to account for the additional loss in the film in the rotational drag experiments. The current flow shown in Fig. 6(b) is likely to provide almost no shielding, and one would expect the ratios shown in Fig. 4 to be higher. This leaves the most likely alternative for the current flow as that shown in Fig. 6(c). Such a current distribution would provide some shielding under the center of the film but would provide additional field under the perimeter of the film. While this seems the most likely explanation at present, final resolution of the detailed current distribution awaits further experimentation.

CONCLUSIONS

We measured rotational drag of a PM/HTS bearing that used either an HTS thin-film, bulk HTS, or combination of film over the bulk. In all cases the rotational drag was velocity independent, consistent with a hysteretic energy loss. The rotational drag contributed by the film was much higher than expected. We then measured the shielding properties of the HTS film for different angles of an AC excitation coil. The results showed that the film shields well when the magnetic moment of the coil is perpendicular to the film surface, but it does not shield well when the moment is parallel to the plane of the film. All of the results are consistent with the inhomogeneity of the PM magnetic field having a substantial horizontal component. For horizontal components, the low aspect ratio of the film geometry results in current flow extending over a much larger surface area than is required by a bulk HTS, and the expected losses and poor shielding in this case are consistent with the experimental results.

1. J. Hull, *JOM* **51**(11), 13 (July 1999).
2. B. Lehndorff, H.-G. Kurschner, and B. Lucke, *Appl. Phys. Lett.* **67**, 1932 (1995).
3. B.R. Weinberger, *Appl. Supercond.* **2**, 511 (1994).
4. P. Schonhuber and F. C. Moon, *Appl. Supercond.* **2**, 523 (1994).
5. B. Lucke, H.-G. Kurschner, B. Lehndorff, M. Lenkens, and H. Piel, *Physica C* **259**, 151 (1996).
6. T. H. Johansen, A. B. Riise, H. Bratsberg, and Y. Q. Shen, *J. Supercond.* **11**, 519 (1998).
7. B. R. Weinberger, L. Lynds, Jr., and J. R. Hull, U.S. Patent No. 5,086,034 (1993).
8. B. R. Weinberger and L. Lynds, Jr., U.S. Patent #5,256,638 (1993).
9. J. R. Clem, *Adv. Supercond. X* 1:23 (1997).
10. A. Cansiz and J. R. Hull, to appear in Proc. Cryog. Eng. Conf., Montreal (July 1999).
11. J. R. Hull, T. M. Mulcahy, K. L. Uherka, R. A. Erck, and R. G. Abboud, *Appl. Supercond.* **2**, 449 (1994).
12. J. R. Hull, T. M. Mulcahy, and J. F. Labataille, *Appl. Phys. Lett.* **70**, 655 (1997).
13. E.H. Brandt, Superconductor disks and cylinders in an axial magnetic field. I. flux penetration and magnetization curves, *Phys. Rev. B* 58:6506 (1998).
14. A. Rastogi, H Yamasaki, and A. Sawa, Surface quality effects in hysteretic magnetization of $YBa_2Cu_3O_{7-\delta}$ films, *Adv. Supercond. X* 1:561 (1997).
15. X.N. Xu, A.M. Sun, M.J. Qin, S.Y. Ding, X. Jin, X.X. Yao, and S.L. Yan, Current and magnetic field distribution of disk-shaped superconducting film, *Physica C* 291:315 (1997).