ULTRALOW FRICTION IN A SUPERCONDUCTING MAGNETIC BEARING

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SUMMARY

Passive levitation by superconducting magnetic bearings can be utilized in flywheels for energy storage. Basic design criteria of such a bearing are high levitation force, sufficient vertical and horizontal stability and low friction. A test facility was built for the measurement and evaluation of friction in a superconducting magnetic bearing as a function of operating temperature and pressure in the vacuum vessel. The bearing consists of a commercial disk shaped magnet levitated above single grain, melt-textured YBCO high-temperature superconductor material. The superconductor was conduction cooled by an integrated AEG tactical cryocooler. The temperature could be varied from 50 K to 80 K. The pressure in the vacuum chamber was varied from 1 bar to 10^{-5} mbar. At the lowest pressure setting, the drag torque shows a linear frequency dependence over the entire range investigated ($0 < f < 40$ Hz). Magnetic friction, the frequency independent contribution, is very low. The frequency dependent drag torque is generated by molecular friction from molecule-surface collisions and by eddy currents. Given the specific geometry of the set-up and gas pressure, the molecular drag torque can be estimated. At a speed of 40 Hz, the coefficient of friction (drag-to-lift ratio) was measured to be $\mu = 1.6 \times 10^{-7}$ at 10^{-5} mbar and T = 60 K. This is equivalent to a drag torque of 7.6×10^{-10} Nm. Magnetic friction causes ~1% of the total losses. Molecular friction accounts for about 13% of the frequency dependent drag torque, the remaining 87% being due to eddy currents and losses from rotor unbalance. The specific energy loss is only 0.3% per hour.

INTRODUCTION

A cooled superconductor can transport electrical currents without any losses. The new high temperature superconductor (HTSC) $YBa_2Cu_3O_7$ (YBCO), prepared by melt-texturation, has another extraordinary ability: It exhibits strong flux pinning and can trap magnetic fields. Due to this effect, a magnetic cushion is generated between a permanent magnet and the superconductor. This cushion provides stable levitation with vertical and horizontal restoring forces and almost frictionless rotation of the magnet. In contrast to conventional (low-temperature) superconductors, high-temperature superconductors require cooling by liquid nitrogen only (T = 77 K). They are more cost-effective and closer to practical applications. Active magnetic bearings have proven to be practical for rotating machinery. In contrast to those active systems which require elaborate control circuits to be operational, superconducting bearings are completely passive. Possible applications in the electric utility field are power systems, such as efficient high-speed flywheels for energy storage. Desirable properties of a bearing for a flywheel are high levitation forces, sufficient vertical and horizontal stiffness and low intrinsic drag.

The force F acting on a magnetic dipole m in an effective field H^{eff} is given by:

$$\vec{F} = -\mu_0 \nabla(\vec{m}\vec{H}^{eff}) \tag{1}$$

where μ_0 is a constant. Assuming the magnetic moment m is constant, the force in vertical direction, the levitation force F_z is:

$$F_z = -\mu_0 \Big(\sum_{i=x,y,z} m_i \frac{\partial H_i^{eff}}{\partial z} \Big) \tag{2}$$

here m is the magnetic moment of the superconductor, x, y, z represent the three geometric axes. According to (2), the levitation force F_z depends upon both m_i and H^{eff}. In the approximation of Bean's model [1], for a given effective magnetic field H^{eff}, the magnetic moment m_i of the superconductor in the critical state is proportional to the critical current density J_c and to the size of the shielding current loop d:

$$m \propto J_c \cdot d \tag{3}$$

Thus, high levitation forces and stiffness require a high effective magnetic field H^{eff} with high first and second order spatial derivatives and a superconductor with a large magnetic moment (i.e. high critical currents flowing over a considerable area). For melt-textured YBCO, macroscopic J_c values are typically around several 1000 A/cm^2 and d is several cm. H^{eff} should be at least several KOe. Preferably, permanent magnets based on Sm-Co or Nd-Fe-B compounds are used in the bearings.

Hysteresis loss in the superconductor is one of the main contributions to intrinsic bearing drag [2-4]. It is attributed to inhomogeneities in rotational symmetry of the permanent magnet. According to Beans' law [1], the energy loss due to magnetic drag for a superconductor in the critical state is given by:

$$E_{mag} \propto \frac{(\Delta H^{eff})^3}{J_c} \tag{4}$$

where ΔH^{eff} is the magnetic field inhomogeneity.

In order to establish an optimized bearing design, several studies have evaluated model bearing configurations. Bulk YBCO pellets were combined with permanent magnets of different size and geometry and in various configurations [5-7]. These experiments concentrated on studying static and dynamic interaction forces. The motivation for the work we report in this paper was to see to what extent friction can be reduced in a superconducting magnetic bearing. Minimum bearing friction is of particular importance in a flywheel system for diurnal load leveling. The goal for such a system is a net loss due to friction of 0.1% per hour (2.4% per day) [8]. Of course, in a flywheel system, other sources of friction exist such as eddy current drag and aerodynamic drag. Both depend upon frequency and can be quite high at high speeds. Nevertheless, the minimization of magnetic bearing drag is important. Not only does E_{mag} contribute to the overall friction in the system, but because it occurs in the superconductor, it presents an additional load for the cooling system.

According to eqn (4), magnetic drag can be reduced by using a homogeneous permanent magnet combined with a bulk superconductor with high J_c. Since J_c is known to increase with decreasing temperature, operation of the bearing at reduced temperatures is expected to further decrease E_{mag}.

EXPERIMENTS

Experimental Set-Up

Experiments were conducted in a vacuum chamber evacuated by a turbo molecular pump. The chamber is 9 cm in diameter and 7 cm high. Pressure could be set between 10^{-6} mbar and 1 bar. A bulk HTSC sample was placed on a cold plate and mounted on top of a cold finger. Cooling was provided by a AEG tactical cryocooler [9]. The hot end of the cold finger, outside the vacuum chamber, was air cooled using a small ventilator. Temperature sensors were located near the cold plate at the bottom of the sample holder and near the top of the sample. The lowest temperature reached was 40 K. We found this to be strongly dependent upon a series of experimental conditions, such as quality of the vacuum and ambient temperature in the lab (the efficiency of the stirling cryocooler depends upon the temperature at the warm end of the cold finger). During cool down, the permanent magnet was fixed in position by a movable holding and positioning device. When the HTSC element had reached the desired temperature, the device was retracted and the magnet was released (field cooled procedure). Spin-ups were accomplished with a valve controlled gas nozzle placed near the magnet using dry nitrogen gas. After the spin-up the position of the nozzle was lowered to avoid any interference with any possible gas streams that might leak through the valve. Rotational speeds were measured through a quartz window on top of the vacuum chamber using a LED sensor unit. During spin-down, speed, temperature and pressure were continuously monitored by a computerized data acquisition system.

A cool down experiment with a 80 g bulk HTSC sample is shown in Fig. 1. The sample cold plate alone gets cold in about 20 min. For better insulation and reduction of thermal losses, the superconductor had been wrapped in superinsulation foil. Still, a difference of about 2 K was measured between upper and lower sensor. We ascribe this difference which was observed for all experiments to losses by thermal radiation from the walls of the vacuum chamber.

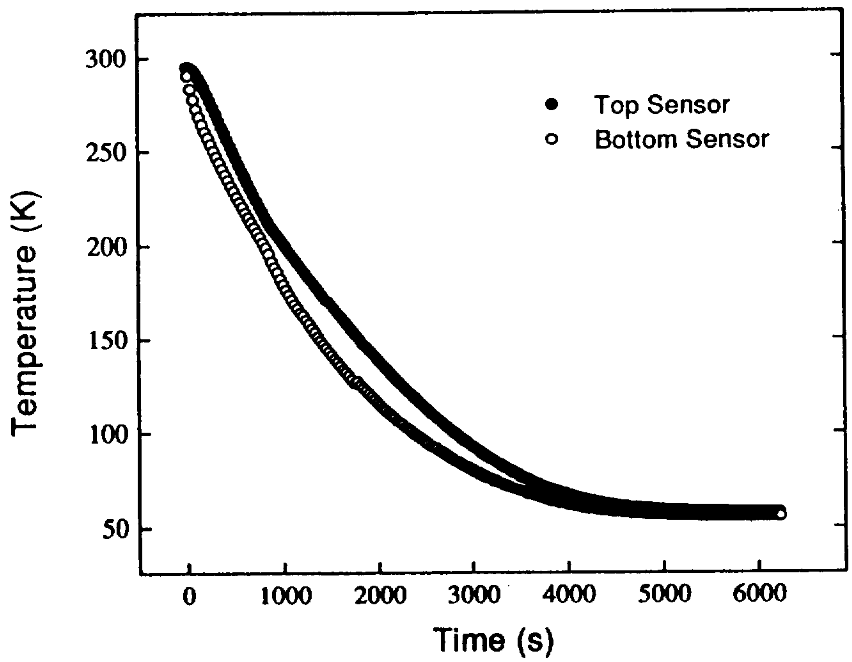

Fig.1: Cool down experiment for a 80 g bulk HTSC element. The difference in temperature between top and bottom temperature sensor is due to losses by thermal radiation from the walls of the vacuum chamber.

Spin-Down Experiments

A series of spin-down test was conducted with a homogeneous, disk shaped permanent magnet, measuring ø 25 mm x 9 mm high. The HTSC element was made of single grain, top seeded, melt-textured YBCO. Its dimensions were ø 32 mm x 17 mm high. With the magnet in place, the superconductor was cooled. Then the magnet was released and accelerated to a given speed up to 40 Hz. In Fig. 2 (a), a spin-down run from 35 Hz is shown for a pressure of 1 bar. Bearing gap, the distance between the upper surface of the HTSC element and the bottom of the magnet disk, was 6 mm, the surface temperature of the HTSC element was 60 K (top temperature sensor). Apparently, friction is very high. In only 45 min the freely rotating magnet disk was decelerated from 35 Hz to 0. The result of a similar experiment but in a vacuum of 10^{-5} mbar is presented in Fig. 2 (b). At this low pressure, friction is so low that a complete spin-down from 35 Hz was not practical. Instead, we started the experiment at the low frequency end. The magnet was accelerated and spin-down was recorded over a time period of about an hour. Then the magnet was accelerated again to the next higher frequency and so on. The insert shows

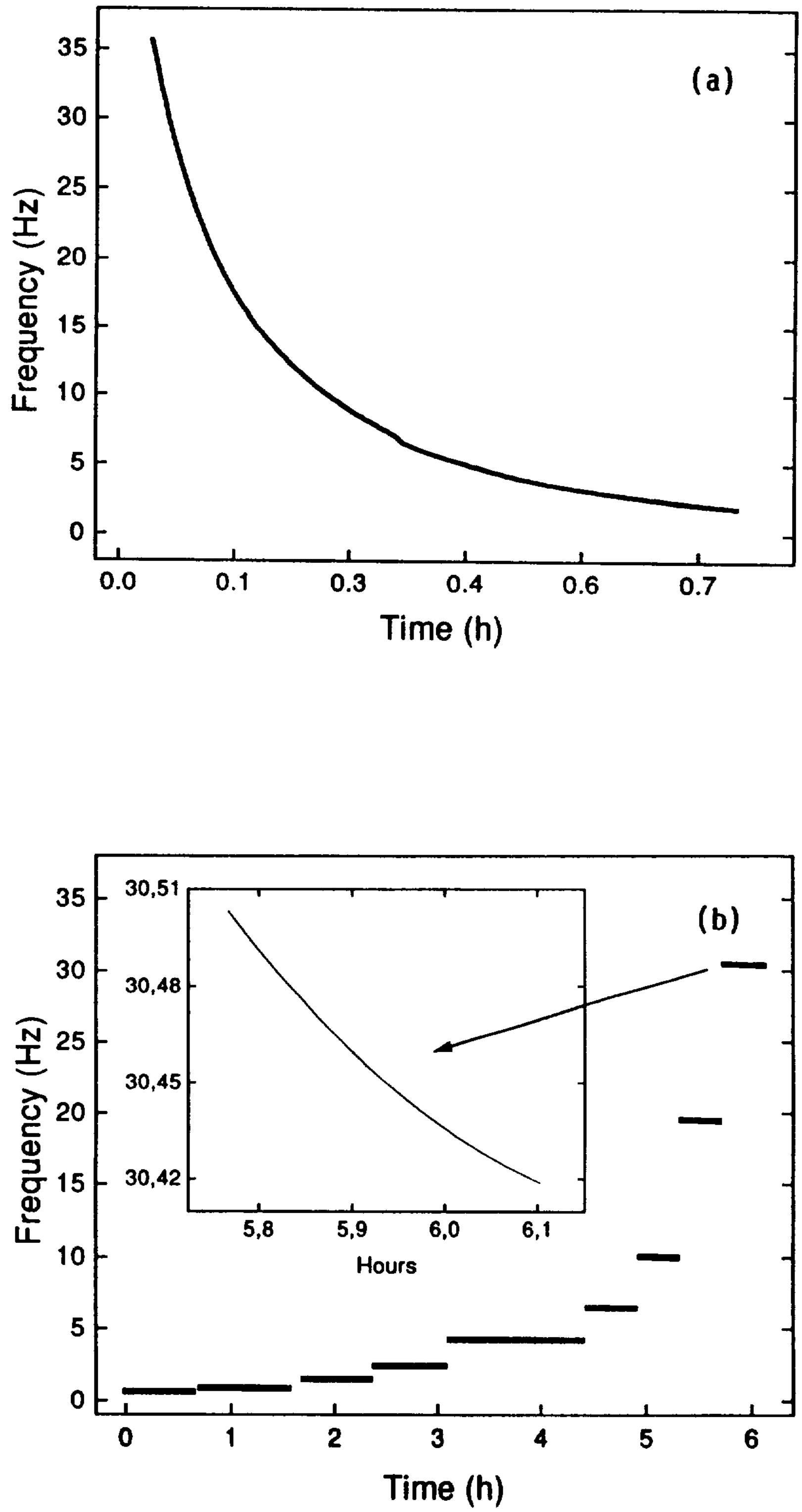

Fig. 2: Spin-down experiments at 60 K, bearing gap was 6 mm. (a) Pressure was 1 bar, (b) pressure was 10^{-5} mbar. The insert shows the spin-down from ~30 Hz on an expanded scale.

the spin-down recorded from ~30 Hz. It takes about 20 min for the frequency to drop by 0.09 Hz. The non-linearity of the curve indicates that there are frequency dependent contributions to the overall drag, such as molecular drag and eddy current drag.

Drag torque and coefficient of friction μ (drag-to-lift ratio, defined in [10]) vs frequency in the range from 0 to 40 Hz are shown in Fig. 3. Pressure in the vacuum chamber was 2 x 10^{-5} mbar, the temperature of the HTSC element was 60 K. Gap width was 7 mm. The drag torque shows a linear frequency dependence over the entire range indicating frequency dependent and frequency independent contributions to the total drag. The frequency independent contribution is due to magnetic hysteresis losses in the superconductor. From a least-squares fit to the data the magnetic drag torque Γ_{mag} was deduced. We find Γ_{mag} = 7.3 x 10^{-12} Nm. The frequency dependent contribution increases with increasing frequency. Eddy current losses, molecular drag and drag due to rotor unbalance are the main sources of frequency dependent drag [11]. At f = 40 Hz, the total frequency dependent drag torque was measured to be 7.6 x 10^{-10} Nm. Using the analytical expression derived by Chambers et al. [12] the molecular drag torque expected for our set-up can be calculated. We find Γ_{mol} = 1 x 10^{-10} Nm which is only 13 % of the frequency dependent contribution. Apparently, rotor unbalance and eddy currents give a significant contribution to the frequency dependent losses.

Nevertheless, friction is very low. At f = 40 Hz, the specific energy loss given by

$$\Delta E_{loss} = \frac{df}{dt \cdot f} \cdot 3600 \frac{s}{hour} \cdot 100\% \text{ (in \% per hour)} \qquad (5)$$

is only 0.3 % per hour.

The temperature dependence of the magnetic friction was deduced from measurements at frequencies below 1 Hz. With decreasing temperature, the energy loss E_{mag} due to magnetic drag is expected to decrease according to eqn (4), because J_C increases. Comparing the results at 60 K as shown in Fig. 3 (b) to a run made under identical conditions at 78 K, we find that E_{mag} is about 40% lower at 60 K. This is somewhat less than expected since intragrain J_C values typically increase by about a factor of 2, going from 77 K to 60 K, which should have resulted in a reduction of about 50% for E_{mag} according to eqn (4).

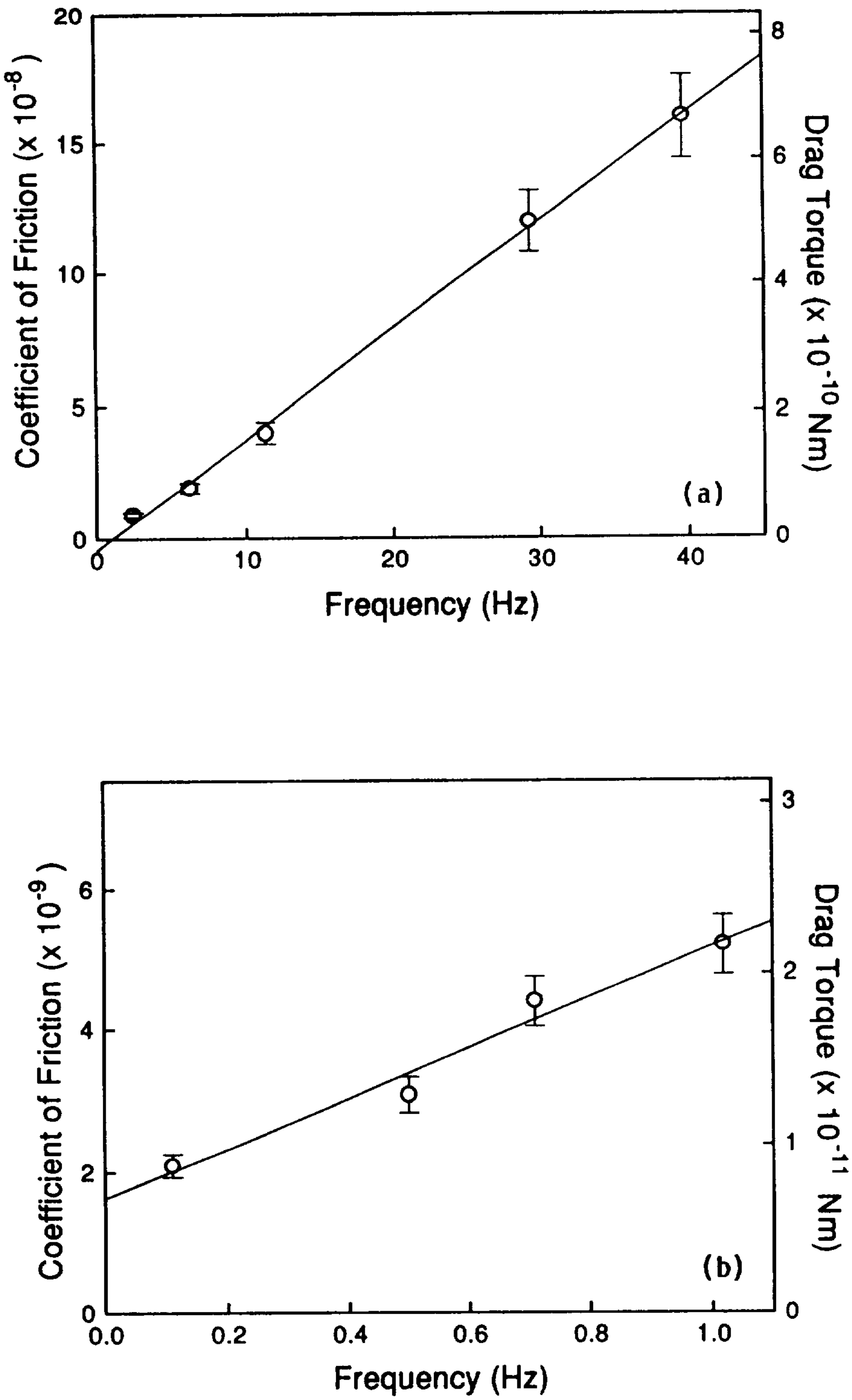

Fig. 3: Coefficient of friction μ and total drag torque vs frequency at T = 60 K. Pressure was 2×10^{-5} mbar. Gap width was ~7 mm. The solid curve is a linear least-squares fit to the data.

CONCLUSION

In conclusion, we have conducted a series of spin-down experiments with a superconducting magnetic bearing. Friction was studied as a function of operating temperature and pressure in the vacuum chamber. At atmospheric pressure, the drag torque due to gas friction is very high. At the lowest pressure setting (10^{-5} mbar), the drag torque shows a linear frequency dependence. For our set-up, using a homogeneous permanent magnet disk and a single grain HTSC element, magnetic friction was found to be insignificant compared to the other loss mechanisms. The experiments indicate that a further reduction of energy loss is accomplished by reducing eddy current and molecular drag.

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