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6. AUTHOR(S)
Wei-Kan Chu and Ki Ma

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TCSUH
University of Houston
Houston, TX 77204-5932

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Dr. Harold Weinstock
AFOSR
801 North Randolph Street, Room 732
Arlington, VA 22203-1977.

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14. ABSTRACT

We have studied the fasibility of using High Temperature Superconducting levitation bearings for Flywheels and momentum wheels in energy and momentum storage for space applications. We have constructed a small flywheel prototype to demonstrate the principle. Measurement of small residual losses in HTS levitation bearings so as to be able to optimize design parameters to keep the losses to the lowest possible. There are two distinct loss mechanisms: magnetic hysteresis in HTS, or eddy currents in the rotating magnet. There are three parts to our study efforts: measurement of torque in a simple HTS levitation bearing with a non-axisymmetric magnet to study hysteresis loss in HTS, development of instrumentation capable of detecting varying magnetic field in reference frame co-rotating with magnet – to study eddy current loss in magnet, modeling and computation to provide understanding and direction to the experimental efforts. Impact on cryocoolers to the overall power consumption are estimated. All studies are summerized in a set of preprints to be published. (See attachments).

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19a. NAME OF RESPONSIBLE PERSON
W.K. Chu <wkchu@uh.edu>

19b. TELEPHONE NUMBER *(include area code)*
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High Temperature Superconductor Levitation Bearings for Space Application

K. B. Ma, Q. Y. Chen, E. Postrekhin, H. Ye, Y. Zhang, and W. K. Chu, Dept. of Physics and Texas Center for Superconductivity, University of Houston, Houston TX 77204, USA

Abstract:

High temperature superconductors (HTS) have enabled us to construct non-contact levitation bearings for flywheel application. A flywheel with low loss bearing is important in energy storage for space applications where energy consumption and power consumption is carefully budgeted. It is interesting to know that a set of flywheels is commonly used for angular momentum storage for satellites pointing system. In this paper, we will discuss the design criterion on a small stable pointing system using levitation wheels. This is achieved by using superconductor magnet bearings (SMBs) which are passive, and virtually frictionless. We will also address frequently raised issues related to cooling requirement when using a cryocooler.

1. INTRODUCTION:

A high temperature superconductor (HTS) levitation bearing is made out of a permanent magnet bearing about an axis of azimuthal symmetry in the vicinity of a bulk piece of high temperature superconductor cooled sufficiently to be in its superconducting state. The rotating permanent magnet is kept in an equilibrium position by the action of flux pinning forces in the bulk HTS. There is no direct physical contact between the rotating permanent magnet and the HTS. One obvious advantage of such non-contact bearings is that there is no wear and tear, hence they can be expected to last a long time. Less obvious, but more significant is the fact that these bearings have extremely low loss, and therefore generate very little heat during operation. Thus the power that is required to go into sustaining the rotation of the bearing is also correspondingly low. Moreover, this HTS levitation bearing functions in a passive manner without the need for active electronic control, in contrast with modern day active magnet bearings. This also represents a savings in power consumption. It also makes the HTS levitation bearing more reliable in the sense of having less components that could fail.

The characteristic of low power consumption in the operation of HTS levitation bearings makes them very attractive in space applications onboard miniature spacecraft where power supply is naturally scarce. The long lifetime expected of HTS levitation bearings is also helpful in extending the useful lifetime of the spacecraft itself. One such application is for energy storage with flywheels, offering a competitive alternative to electrochemical batteries. Negligible bearing loss stretches energy storage times with flywheels to respectable lengths. In terms of charge-discharge cycles, flywheel energy storage wins over batteries by a large margin.

On top of the above application, the wheel is the natural and only option in another space application-attitude control. The application of HTS levitation bearings allows momentum wheels to be made smaller and faster, or the power required to sustain their rotation be significantly reduced. Furthermore, further efficiency in equipment usage can be gained when the same set of wheels is used for both attitude control and energy storage. Performance goals for precise positioning and attitude determination are 0.01 deg accuracy or better, high frame rate (~ 60 hz), and high angular rate of 0.2 deg/sec. While sufficient torque to achieve satisfactorily rapid slew rates and stabilization of the spacecraft can be obtained with present day reaction wheels, it is imperative that the vibration of the spacecraft induced by the reaction wheels be reduced by an order of magnitude to allow high resolution imagery. It is also important to reduce the size and weight of the pointing system so that it can be fitted onto mini-satellites that are much less costly to launch and enjoy more flexibility in scheduling and positioning.

2. PREVIOUS WORK AND CURRENT STATUS OF THE FIELD:

We have studied the interaction between magnets and superconductors. We successfully demonstrated [1,2] a 19 kg prototype flywheel for energy storage purposes (see Figure 1). The flywheel was spun up to 6000 RPM under a vacuum of 2×10^{-6} torr. Left by itself, the wheel continued to rotate for more than 140 hours. The average power dissipation during that period amounted to no more than 60 mW. This is a clear indication that the friction of the SMB is extremely low, and hence bearing loss is negligible. We could reduce this to a mere 8 mW, if we had a magnet with 1.5% instead of 3% non-uniformity around its circumference. At top speed, the angular momentum stored was 45 J-sec. Vibration amplitudes of the wheel itself were monitored and typical values are, for example, 0.1 mm or less at 1000 RPM. This converts to an overall vibration level at about 0.1 g. (see comparison with commercial wheels in Table 1 below)

A preliminary investigation [3] of the vibration isolation properties of SMBs was carried out with a test mass of 130 gm of superconductor levitated by a ring magnet. The transmission of vibrations of the ring magnet to the levitated superconductor was shown to drop rapidly for frequencies above the natural frequency of the levitated superconductor, at 5 hz. Extrapolating this to a reaction wheel of 5 kg mass, this natural frequency would drop down to the sub-hertz regime, and good vibration isolation can be expected for frequencies above 1 hz. The transmissibility at 60 hz. is 30 to 40 db down from the case where the superconductor is warm and sits directly upon the magnet. Together with the vibration amplitudes observed on the wheels stated earlier, this indicates that the wheel is not likely to be an appreciable source of mechanical vibration noise.

As an intermediate step towards the development of reaction wheels using SMBs, we have fabricated small aluminum momentum wheels, with a diameter of 5" and a mass of 1 kg. (see Figure 2) Using these, we showed that it is feasible to maintain speed with a standard 9 V dry cell battery. The wheel was run at a steady speed of 60 RPM in air, with an estimated drag torque due to windage that corresponds to the level experienced when the wheel is spun at 12,000 RPM in vacuum. The peak power consumption was 250 mW, while the average was 25 mW. This level of power consumption is lower than that required to keep the superconductors cold enough (77 K or lower) for the bearing to work. Nevertheless, we can still expect to reduce this further by a factor of 10 by using a more uniform permanent magnet.

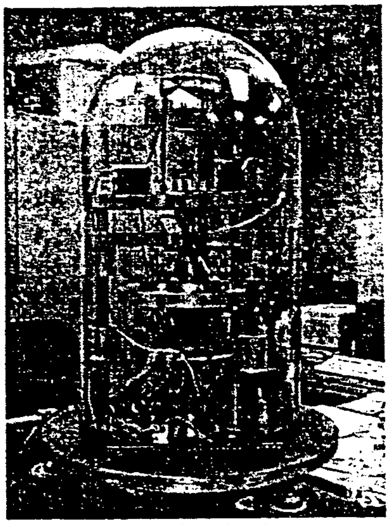
Figure 1: 19 kg flywheel energy storage system

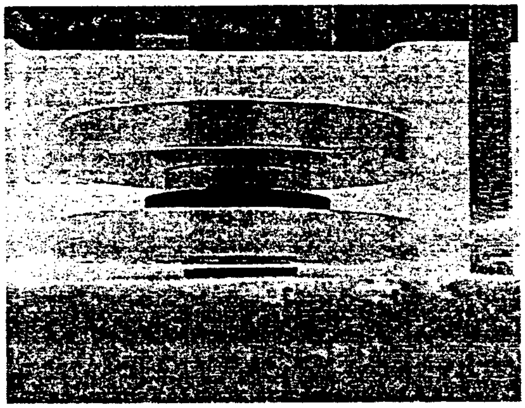
Figure 2: 1 kg momentum wheel levitated on SMB

3. BEARING COMPARISON AND ISSUES RELATED TO CRYOCOOLERS:

With the use of SMBs, a main drawback pointed out above is that an additional need for power stems from the necessity to maintain low temperatures (77 K) for the superconductors to work. The temperatures encountered in orbit (120 K at GEO, 250 K at LEO), are not low enough. To bridge this gap, we have identified a small cryocooler on the market that has a cooling power of 0.25 W at 80 K, with an input power of less than 6 W. The cryocooler has a mass of 0.45 kg only, which is less than half the mass (1.2 kg) of a single wheel itself. The main body of this cryocooler occupies a cylinder of 55 mm diameter, 65 mm high. This one unit alone should fulfill our cooling requirements for a four wheel system (0.12 W at 77 K, input 2.8 W) with margin to spare. While this is the dominant component of power expenditure for this system, it still leaves us with a significant savings in power. This important point is further borne out by comparing the power loss and stopping times for identical wheels operating under identical requirements, but using different types of bearings, in Table 1.

Table 1: Comparison of power loss and stopping time for a 3.5 J-sec reaction wheel with different bearings.

Bearing type	Ball bearings BATC[a]	Ball bearings SMEX[b]	Active bearings[c] Laminated rotor	HTS bearings
Angular Momentum	2.5 J*sec	3.4 J*sec		3.5 J*sec
Speed	2500 RPM		(32000 RPM)[c]	31500 RPM
Reaction Torque	29 mN*m	140 Mn*m		18 mN*m
Weight	3.43 kg	3.86 kg		1.2 kg
Diameter	23.11 cm	20.32 cm		7.0 cm
Height	8.636 cm	10.16 cm		7.0 cm
Power against drag at top speed	Not itemized	Not itemized	2.2 watt	0.026 watt[d]
Radiative heat leak rate				0.003 watt[e]
Power for electronics	Not itemized	Not itemized	Not available	0
Power required for cooling				0.68 watt[f]
Total Sustenance Power	9 watt	6 watt	> 2.2 watt	0.71 watt
Peak Power		45 watts		42 watts
Stopping Time		33 min	90 min	5.3 days[g]
Overall Vibration Levels (RMS)	13 g			0.1g[h]

[a] The BATC design is a commercial reaction wheel product from Ball Aerospace & Technologies Corp.

[b] The SMEX is one of the convention wheel designs (Charles Clagett, NASA Goddard).

[c] Power loss is extrapolated to 32000 RPM from data at speeds below 15000 RPM in reference [5]. Only the iron loss in a laminated rotor was accounted for. Other power requirements such as that of the control electronics have not been included.

[d] This loss assumes a circumferential magnet uniformity of 1%. This loss is at 77 K and equivalent to 0.1 watts when converted to 308 K.

[e] This estimation is based on emissivity of 0.02 for the surface of the enclosure for the superconductors and an environmental temperature of 120 K at GEO.

[f] A single 0.45 kg unit Hymantic cryocooler takes 6 watts to remove 250 mW for all environmental temperatures below 30 °C.

[g] Extrapolated from our previous flywheel work, see reference [2].

[h] Vibration level here is measured directly off a 19 kg flywheel, amplitude 0.1 mm at 1000 RPM [6].

The passive aspect of the SMB also means that no extra power is needed to stabilize the rotating wheel during steady operation. In practice, a minute amount of the kinetic energy stored in the wheel will be dissipated, and a correspondingly minute amount of power input is needed to maintain its speed. This sustenance power required is smaller than comparable systems employing contact bearings or active magnetic bearings by half to one order of magnitude.

At this stage of development, one peripheral piece of hardware that is nevertheless essential to the successful operation of SMBs in most environments is the cryocooler. We have carefully chosen this piece of hardware particularly with space application in mind. Thus, it embodies desirable features such as small mass and volume, low power consumption, long lifetime, manufacturability in large quantities at low cost and space-qualified.

We have listed some issues frequently raised for the application of SMBs in space, and possible solutions in Table 2 below.

Table 2: Frequently raised issues for the application of SMBs in space

Issue	Value	Remark
Cryocooler power consumption	0.7 watt at 120K (GEO); 2.1 watt at 250K (LEO); 3.6 watt at 300K	Rotor loss alone in active magnetic bearings accounts for 2.2 watts. Loss in conventional ball bearings is about 6 watts. Value for SMB is mainly due to radiative heat leak.
Cryocooler volume and/or weight	55mm diameter; 65 mm high; 0.45 kg	Need only one unit for all four wheels. Weighs less than half the weight of one wheel of our design or a third of a typical wheel (see Table 1).
'SMB requires that the magnetic field be axisymmetric about the spin axis,' vs. 'the rotating magnetic field of most motors is not axisymmetric'		Separate the motor magnetic field and the superconductor as far apart as physically feasible;. Increase the number of magnet poles in motor; better design to reduce drag is part of current research.
Rotor dynamics or static/dynamic balancing of wheels running on SMBs		Balancing wheels running on SMBs is the same as those running on conventional bearings. The wheel can easily be brought to operate in the supercritical regime where it is self-centering to some degree. So, balancing is not as critical. This is further discussed in reference [6]. Same applies to magnets on the wheel – i.e. requirement is not difficult to satisfy.
Effect of SMB mechanical vibrations to the spacecraft		Wheels running on SMBs are surprisingly quiet, mechanically. For more quantitative details, please see references [3] and [6].
Long term reliability of SMBs		No intrinsic limitation to the functional lifetime of SMBs are known.

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Axial Force in a Superconductor Magnet Journal Bearing

E.Postrekhin, Chong Wang, Ki Bui Ma, Quark Chen, and Wei-Kan Chu

Texas Center for Superconductivity, University of Houston, Houston, TX 77204

Using superconductors and magnets, a journal bearing could be made from a permanent magnet cylinder in a superconductor ring, We have assembled a prototype superconductor magnet journal bearing of this configuration, and investigated the behavior of the axial force that it can provide. We have put together a numerical model of the interaction between the permanent magnet and the superconductor that is capable of describing these experimental results semi-quantitatively. Combining direct experimental measurements and using the numerical models proposed, we have achieved a qualitative understanding of the behavior of the axial force and its relationship of to the dimensions of the magnet and material quality such as the homogeneity of the superconductor that constitute the bearing.

1. INTRODUCTION

High T_c superconductors (HTS) combined with permanent magnets (PM) have been used to fabricate bearings in applications that are fruitful only if the level of power loss can be kept as low as possible, such as kinetic energy storage using flywheels. Most previous investigations have focussed on thrust bearings that provide support against gravity, commonly known as levitation bearings. Here, our study turns to journal bearings, whose purpose is to provide constraining forces that confine a rotating axis to desired position and direction. Nevertheless, unbalanced loads along the axis inevitably exist, and a journal bearing has to provide balancing forces to prevent the rotor from slipping away in the axial direction. Our study of journal bearings starts with their capability to provide these axial forces.

2. MODEL

One way to make a journal bearing out of HTS and PM is to put PM cylinder in HTS ring, as in Fig. 1. The behavior of the axial force between HTS and PM in this system can be roughly subdivided into the following three regions: (a) PM entering hole in HTS ring, (b) PM inside hole in HTS ring and (c) PM exiting from hole in HTS ring. In region (a), the behavior of the axial force can be expected to be similar to PM levitated above HTS disks as in thrust bearings, with a slower rise as the top surface is approach due to the absence of HTS material in the hole of the HTS ring, compared to an HTS disk. In region (b), apart from end effects, the axial force is expected to be a constant drag force similar to that encountered in the case of a PM moving over a plane HTS surface at constant height. The behavior in region (c) is more diverse, and depends on the extent to which magnetic flux has been allowed to penetrate the HTS ring so far. If the penetration of flux has not been extensive, as with weak magnets or high J_c HTS rings, then the axial force between HTS and PM is repulsive, as if the HTS ring is a strong diamagnetic material. In cases with more extensive flux penetration, the effect of magnetic relaxation is to render the condition more akin to the case of field cooling the PM inside the hole of the HTS and then pulling it out. In other words, the axial force between HTS and PM becomes attractive. In such cases, the drag force while the PM is in the hole in region (b) can be expected to be high, and the attractive force as the PM is pulled out into region (c) can regarded as a gradual diminution of this drag force as the PM leaves the HTS ring. This is illustrated in Fig. 2, which is a numerical

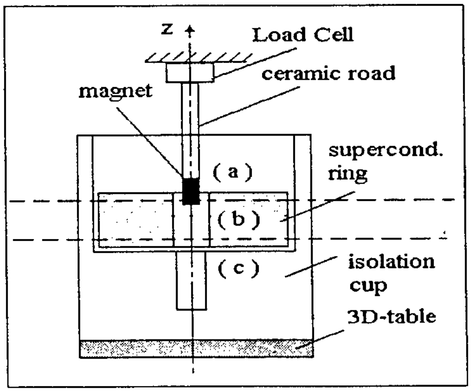

Figure 1. The setup for measurement of the axial force between superconducting ring and cylindrical magnet.

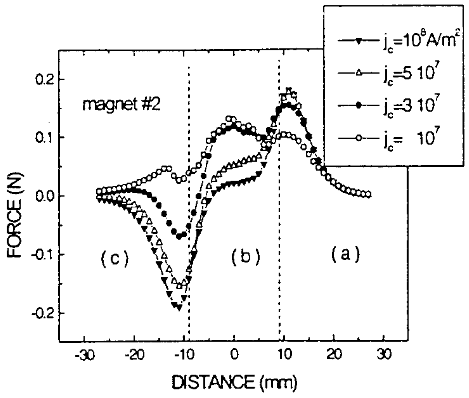

Figure 2. Numerical calculation of the axial force between the HTS ring and the magnet

calculation for the case of the HTS ring and one of the PM used in our experiments. Behavior with respect to varying degree of flux penetration is simulated by assuming different values of the critical current density of the HTS material.

3. EXPERIMENT

We have investigated the axial force between an HTS ring and three different PM. The HTS ring is a $YBa_2Cu_3O_7$ sample that was prepared by melt-texturing together with seeded directional solidification. The superconducting ring had an outside diameter of 40mm, inside diameter of 16mm and a height of 20mm. The critical current density of the sample was measured by a four contact impulse method and found to be of the order of 10^8 A/m^2 at 77 K. All three magnets, PM #1, PM #2, and PM #3, used in this work has the same diameter of 6.3mm, but with different heights at 3.5mm, 6.3mm, and 14mm. The magnetic flux densities at the center of the pole faces of these magnets are 2.04 kG, 2.81 kG and 4.71 kG, respectively. The axial force was measured with a Precision Miniature load cell in the setup shown in Fig. 1. The results of these measurements are shown in Fig. 3.

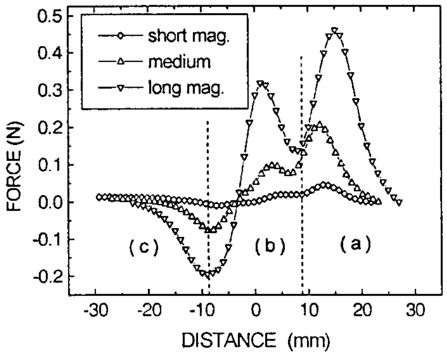

Figure 3. The experimental dependencies of the axial force vs distance.

4. DISCUSSION

The experimental results show the same features in broad outline as the numerical calculation. Thus, we can identify regions (a), (b) and (c) corresponding to the PM entering, being inside and exiting the hole in the HTS ring, respectively. The PM experience a repulsive force on entering and exiting. The 'PM inside' region (b) is flat in the case of PM #1. For PM #2, a trough and a peak begins to develop. This becomes more evident for PM #3. On the whole, we can argue that the behavior observed is closer to that expected of small or moderate amount of flux penetration. Two reasons can be offered for the behavior in region (b). One is that PM #2 and PM #3 are progressively longer, and therefore, region (b) becomes shorter, as either magnetic pole is nearer to the corresponding HTS flat surface for the longer magnet as they pass through the hole. The other is that the material is inhomogenous as regards to its critical current density, at different points along the hole and throughout the bulk of the ring. The observed trough and peak could be due to a layer in the middle that has a smaller critical current density and hence assume the characteristics expected of more extensive flux penetration with a stronger magnetic field from a longer PM #3. The observations that we have made indicate that the interaction force between PM and HTS is more susceptible to the effects of sample imperfections on the curved surface inside. The prospect for satisfying specifications accurately for a journal bearing is more demanding than for a thrust bearing. However, our observations have so far been limited to zero field cooled conditions, whereas most practical bearings will be assembled under field cooled conditions, which remains to be investigated.

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Drag Torque of High T_c Superconductor Magnet Bearings with Multi-piece Ring Magnets or Superconductors

E.Postrekhin, Hong Ye, Ki Bui Ma and Wei-Kan Chu

Texas Center for Superconductivity University of Houston, Houston TX 77204, USA

In order for a superconductor magnet levitation bearing to rotate freely, the magnetic field from the magnet must be axisymmetric about the axis of rotation. In contrast, the shape of the superconductor need not be axisymmetric. This allows us to make a large ring of high temperature superconductor out of smaller pieces in the fabrication of superconductor magnet bearings. The problem then arises as to whether the substitution of a single large piece of superconductor by smaller pieces might contribute to additional power loss. We have investigated this by studying the drag torque experienced by multi-piece ring magnets as they turn above multi-piece rings of superconductors, and comparing with results from single pieces of similar sizes. We have coordinated the variation of the drag torque during a turn with the relative orientation of the magnet and superconductor pieces. We use the mean value of the drag torque over several turns as a measure of power loss.

1. INTRODUCTION

Soon after their discovery, high temperature superconductors (HTS) have been used in conjunction with permanent magnets (PM) to construct bearings that are practically frictionless. This makes HTS magnet bearings promising for energy critical applications, such as using them in flywheel kinetic energy storage. The extremely low drag torque observed in HTS magnet bearings depend critically on the extent to which the magnet field from the PM is axisymmetric about the rotation axis. On the other hand, the effect of the HTS not being axisymmetric is small, by comparison. Indeed, it can be readily shown that a PM cylinder can rotate just as freely above several randomly placed HTS disks as above one of them. The practical implication of this observation is that the HTS component of an HTS magnet bearing need not be a single continuous circular piece, but a large piece could be composed of several pieces. The ultimate question is the degree to which a composite HTS piece is equivalent to a single continuous piece. Here, as a starting step to attack this question, we have limited ourselves to a first examination of the behavior of the drag torque and an attempt at understanding its relationship to the field asymmetry of the PM, or the geometrical asymmetry of the HTS component.

2. EXPERIMENT

We have chosen two HTS magnet bearing configurations for study. Configuration A consists of four magnetic disks with the same polarity at the corners of a horizontal square rotating above a single HTS disk. Here the four separate magnetic disks represent a PM which is far from being axisymmetric. This makes the drag torque large enough to give a decent signal. The magnetic disks are NdFeB, with diameter 0.9" and height 0.4". The flux density at the center of a pole face is 3.5 kG. The HTS disk has a diameter of 1.6" and a height of 0.75". The HTS material is of $YBa_2Cu_3O_7$ prepared by a seeded directional solidification method. The material so prepared has a critical current density on the order of 10^4 A/cm^2 at 77 K. The drag

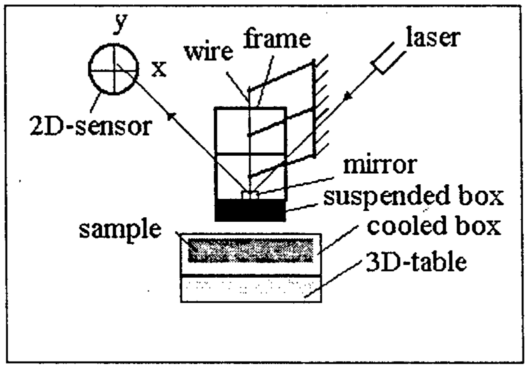

Figure 1. Setup for torque measurements.

torque was measured with the setup shown in Fig. 1, with the gap between the PM disks and the HTS disk at 3 mm and the HTS disk rotated at 0.4 revolutions per minute. In the measurement, the HTS was rotated under the PM disks instead. The measurement was performed under both kind of conditions: field cooled (FC) and zero field cooled (ZFC).

Configuration B consists of a ring magnet above four HTS disks at the corners of a square with 1.9" sides. The ring magnet is of NdFeB also. It has an outer diameter of 1.5" and an inner diameter of 0.5". The flux density at the center is 1.2 kG. The HTS disks has a diameter of 1.1" and a height of 0.6". They were of the same material and has a critical current density of the same order of magnitude as the HTS disk used in configuration A. The drag torque was also measured with the same setup, at the same gap between PM and HTS disks, with the HTS disks rotated under the ring magnet at the same speed. This measurement was performed only under FC condition.

Fig. 2 shows the drag torques measured for configuration A, comparing the results under FC and ZFC conditions. Fig. 3 shows the drag torques measured under FC conditions, comparing the results with configuration A with that in configuration B.

3. DISCUSSION

The drag torque shows oscillations with an offset average value that gives the power loss at this rotating speed (0.4 RPM). As expected, the drag torque from four PM on one HTS disk (configuration A), ~0.025 mNm, is much larger than that from one ring magnet on four HTS disks (configuration B), ~0.002 mNm. Even this small residual drag torque can be attributed to small, but visible imperfections in the ring magnet used. More noteworthy is the observation that the drag torque from four PM on one HTS disk under ZFC conditions, ~0.015 mNm, is smaller than that under FC conditions. This can be understood as a consequence of the interior of the HTS disk being more effectively shielded from the external magnetic field under ZFC conditions. In terms of the pros and cons of ZFC versus FC conditions in bearing design, this consideration favors ZFC conditions.

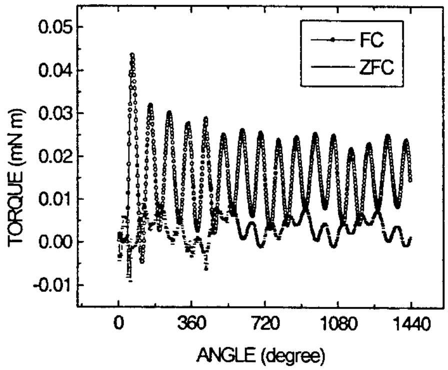

Figure 2. Torque as function of rotating angle at FC and ZFC conditions for configuration 4 magnet one superconductor.

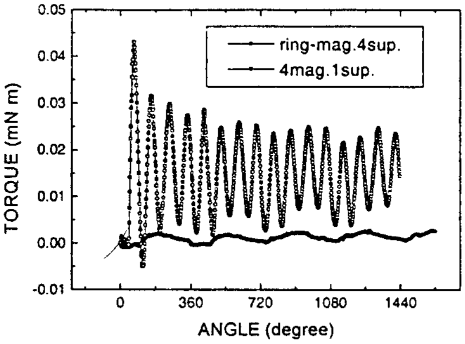

Figure 3. Torque as function of rotating angle

The oscillations of the drag torque can be understood directly as due to uneven trapped field in the HTS disk, reflecting the non-axisymmetric property of the PM. After a few cycles, the transients in the oscillations disappear and the oscillations are reproduced cycle after cycle for many more cycles. Within each cycle, the oscillations show clear correspondence with the number of magnets used in configuration A, but there is no clearly discernible correlation with the number of HTS disks in configuration B, in this case.

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