A FLYWHEEL FOR ENERGY STORAGE WITH FRICTIONLESS HIGH TEMPERATURE SUPERCONDUCTOR BEARINGS

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ABSTRACT

A prototype of a flywheel system with an autostable high temperature superconducting bearing was built and tested. The bearing offered good vertical and lateral stability. A metallic flywheel disk, ø 190 mm x 30 mm, was safely rotated at speeds up to 15000 rpm. The disk was driven by a 3 phase synchronous homopolar motor/generator. Maximum energy capacity was 3.8 Wh, maximum power was 1.5 KW. The dynamic behavior of the prototype was tested, characterized and evaluated with respect to axial and lateral stiffness, decay torques (bearing drag), vibrational modes and critical speeds. The bearing supports a maximum weight of 65 N at zero gap, axial and lateral stiffness at 1 mm gap were 440 N/cm and 130 N/cm, respectively. Spin down experiments were performed to investigate the energy efficiency of the system. The decay rate was found to depend upon background pressure in the vacuum chamber and upon the gap width in the bearing. At a background pressure of $5x10^{-4}$ Torr, the coefficient of friction (drag-to-lift ratio) was measured to be 0.000009 at low speeds for a 6 mm gap width in the bearing.

INTRODUCTION

With the introduction of frictionless magnetic bearings, the efficiency of flywheels for energy storage could be increased to an economically useful level. The main drawback of these bearings is the elaborate control system which is required to keep them operational. Increasing the reliability and reducing the complexity and cost of the system are still points of major concern in the field. For applications which are exceptionally critical concerning fricition, such as flywheel systems for regenerative energy storage, active control is unwanted, because it contributes to intrinsic bearing drag.

These drawbacks do not exist for passive magnetic bearings involving superconducting materials combined with permanent magnets. Such superconducting magnetic bearings can be used for autostable levitation of rotors. Speeds exceeding 250000 rpm have been reported [1]. At present, practical bearing designs are based on the high-temperature superconductor $YBa_2Cu_3O_7$ (YBCO) and can be operated at liquid nitrogen temperature. [2, 3]. Only materials prepared by a specific process, the melt-texturation [4, 5], are useful for magnetic bearing applications. While in terms of maximum attainable levitation pressure and stiffness, the performance of superconducting bearings is still lagging behind active magnetic bearings, coefficients of friction reported for superconducting magnetic bearings are as low as 10^{-6}, and thus about three times lower compared to conventional magnetic bearings.

FLYWHEEL SYSTEM

We built an engineering prototype of a flywheel system with autostable high-temperature superconducting bearings. The system comprises the following components: flywheel disk, superconducting magnetic thrust bearing consisting of a Nd-Fe-B ring magnet (integrated into the flywheel disk) and melt-textured YBCO pellets mounted inside a closed, continuous flow liquid nitrogen cryostat, driving unit including driveshaft with couplings, motor/generator, positioning device and a spring loaded decoupling device, frequency converter, mounting structure, vacuum chamber and vacuum system.

A modular design was chosen for the mounting structure/vacuum chamber. A sensor mounting structure holds a LED sensor unit for monitoring rotational speeds. Inductive proximity sensors are used to measure instantaneous position of shaft and flywheel disk. During operation, the driving unit can be decoupled to study the behavior of the freely rotating disk.

To reduce losses from eddy currents, due to deviations of the field of the rotating magnet from perfect rotational symmetry, the cryostat for the superconductor material was made from fiberglass. A special gluing and sealing technique was developed. Six melt-textured YBCO pellets are mounted inside the cryostat on a non-metallic sample mounting plate. The lid of the cryostat is only 400μm thick for optimum positioning of the ring magnet above the superconductors.

EXPERIMENTS

A metallic flywheel disk, ø 190 mm x 30 mm, 2.5 kg mass, was safely rotated at speeds up to 15000 rpm. The disk was driven by a 3 phase synchronous homopolar motor/generator. Maximum energy capacity was 3.8 Wh, maximum power was 1.5 KW. The dynamic behavior of the prototype was tested, characterized and evaluated with respect to axial and lateral stiffness, damping, decay torques (bearing drag), vibrational modes and critical speeds. The bearing supports a maximum weight of 65 N at zero gap, axial and lateral stiffness at 1 mm gap were 440 N/cm and 130 N/cm, respectively.

Spin down experiments were performed to investigate the energy efficiency of the system. For these experiments, the metallic flywheel disk was replaced by a plastic disk of the same dimensions. A typical spin down experiment is shown in Fig. 1.

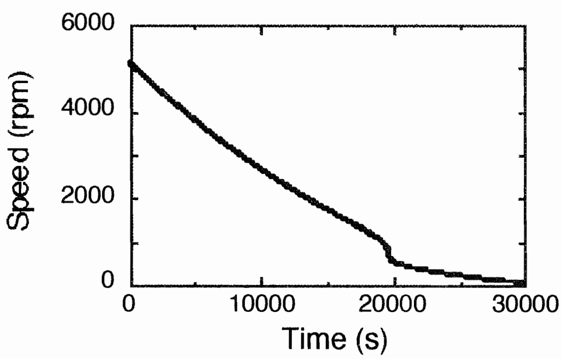

Figure 1: Spin down experiment in vacuum.

The flywheel disk was accelerated to a speed of 5500 rpm. Then the motor was decoupled and the decay of the speed of the freely rotating disk was measured as a function of time. The gap width in the bearing was 6 mm, the background pressure of the Ar gas in the vacuum chamber was $5x10^{-4}$ Torr. For speeds > 2000 rpm, the speed decreases very slowly, almost linearly with time suggesting a constant deceleration rate. During crossing of a resonance near 1000 rpm, the disk decelerates very quickly. For speeds < 400 rpm, the deceleration rate is constant again. The total time for the run was almost 10 hours. From the data the coefficient of friction μ (drag-to-lift ratio) [6] can be calculated. It is found that μ varies from 0.00005 at high speeds to 0.000009 at low speeds.

The drag torque Γ acting on the spinning flywheel disk is proportional to the decay rate $d\omega/dt$, where ω is the angular velocity.

$$\Gamma = J * d\omega/dt \qquad (1)$$

Here J is the moment of inertia of the flywheel disk. From the data in Fig. 1 the dependence of the drag torque upon angular velocity ω can be derived. The result is shown in Fig.2.

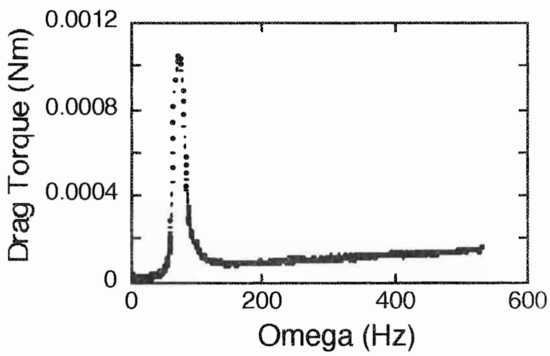

Figure 2: Drag torque vs angular velocity ω as derived from the data in Fig. 1.

The drag torque is found to peak at an angular velocity $\omega \cong 75$ Hz. At the resonance the disk was vibrating laterally with an amplitude of several 100 μm. We found this problem to be associated with a displacement of about 100 μm between the geometric and magnetic axis of the ring magnet. Apparently, at low speeds the magnet ring rotates around its magnetic axis, while at higher speeds the axis of rotation coincides with the geometric axis. The transisiton occurs at around 75 Hz and is connected with additional energy loss.

Above the resonance, the drag torque can be decomposed into a frequency independent and a frequency dependent, linear component. The frequency independent drag torque is attributed to magnetic drag from hysteretic losses of flux line flow in the superconductors [7, 8]. Flux motion in the superconductors occurs when the asymmetric field of the levitated ring magnet is dragged through the superconductors as the disk is rotating. Using the magnetic flux mapping technique, the axial symmetry of the ring magnet was measured to be ±2%. From a fit to the experimental data, the magnetic torque is derived to be $5x10^{-5}$ Nm.

Sources of frequency dependent friction include molecular drag and eddy current losses. Both molecular drag and eddy current losses are expected to increase linearly with increasing speed of the rotor. We find that losses due to molecular drag account for only about 15% of the frequency dependent friction, suggesting that eddy currents in the magnet ring are a major contribution to the frequency dependent drag torque. Nevertheless, our analysis shows that for speeds <

5500 rpm magnetic friction accounts for at least 50% of the total losses.

According to an analysis by Davis et al [9, 10], magnetic friction in a superconducting magnetic bearing is proportional to the third power of the maximum variation of the average magnetic field of the permanent magnet at the superconductors. Thus, a reduction in field inhomogeneity by a factor of two would reduce the magnetic drag torque by almost an order of magnitude. Another major improvement would be a continuous arrangement of superconducting material, in contrast to the discrete configuration we are using for the present prototype. This should not only increase both levitation force and stiffness by about 100%, it would also reduce eddy current losses in the ring magnet by at least an order of magnitude. With these modifications, the present prototype would have a coefficient of friction of several 10^{-7} at 5500 rpm, giving a specific energy loss of < 0.1% per hour.

SUMMARY AND CONCLUSIONS

In summary, we have presented a superconducting flywheel system for energy storage with a superconductor bearing. The bearing offered good lateral and vertical stability. Flywheel disks up to 2.5 kg could safely be rotated at speeds up to 15 000 rpm. The maximum energy capacity was 3. 8 Wh. While overall bearing friction is very low, a significant amount of bearing drag can be attributed to magnetic friction, caused by asymmetries in the field of the ring magnet. Our experiments indicate that further refinement of this technology will allow operation of highly efficient superconducting flywheels in the kWh range.

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