Superconductor-Magnet Bearings with Inherent Stability and Velocity-Independent Drag Torque

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Abstract - **A hybrid superconductor magnet bearing system has been developed based on passive magnetic levitation and the flux pinning effect of high-temperature superconductivity. The rationale lies in the unique capability of a high-temperature superconductor (HTS) to enhance system stability passively without power consumption. Characterization experiments have been conducted to understand its dynamic behavior and to estimate the required motor torque for its driving system design.**

These experiments show that the hybrid HTS-magnet bearing system has a periodic oscillation of drag torque due mainly to the nonuniform magnetic field density of permanent magnets. Furthermore, such a system also suffers from a small superimposed periodic oscillation introduced by the use of multiple HTS disks rather than a uniform annulus of HTS material. The magnitude of drag torque is velocity independent and very small. These results make this bearing system appealing for high-speed application. Finally, design guidelines for superconducting bearing systems are suggested based on these experimental results.

I. Introduction

Many researchers have made efforts to develop levitated magnetic bearings to support rotating structures in the last fifty years. Such levitated bearings are free from friction, mechanical wear, mechanically-induced torque ripple, and energy dissipation, thus resulting in long-life operation with high efficiency and less maintenance. The absence of friction is important in bearing systems. Friction causes not only mechanical wear but also instability in closed-loop systems. Stiction at near-zero velocities causes limit cycling. Coulomb friction is known to cause instability in the feedback control system even though it can extend system stability to some extent by absorbing oscillation energy. Reduced system nonlinearity, such as friction and torque ripple, makes design of the control system easier, rendering a more robust high-performance system [1]. The wear in conventional mechanical bearings has been a major limiting factor in achieving high rotational speed. The lubricants in them are incompatible with operation in clean, vacuum, and extreme-temperature environments.

Despite all these advantageous features of magnetic bearing systems, however, they have inherent open-loop instability as shown by Earnshaw's theorem. A body with magnetization placed in a steady magnetic field cannot rest in stable equilibrium under the action of magnetic forces alone [2]. It makes integration of the control system necessary to achieve a stable magnetic bearing system. Also in active magnetic bearings, bearing loss is proportional to the square of speed, thus causing consumption of a great deal of energy for high-speed operation.

To address these problems, we have developed a levitated hybrid superconductor-magnet bearing system. HTS-magnet bearings passively enhance system stability without power consumption and their bearing drag torque is virtually velocity-independent. No use of active control makes the bearing system simpler, smaller, and lighter, which is important in space applications.

The organization of this paper is as follows: In section II, the interaction between high-temperature superconductor and permanent magnets is described. In section III, characterization experiments are carried out using a prototype hybrid superconductor-magnet bearing system for a lunar telescope azimuth mount. Section IV discusses experimental results and is followed by conclusion and future work in section V.

II. Interaction between High-Temperature Superconductor and Permanent Magnets

It has been more than a decade since the high-temperature superconductor (HTS) was discovered [3]. HTS has a critical temperature of 95 K, which is high enough to be cooled by inexpensive and readily available liquid nitrogen whose boiling temperature is 77 K. The physical properties of a superconductor go far beyond its capacity to carry currents without resistance. A superconductor, when placed in a magnetic field, tries to minimize the magnetic flux density and this kind of material is known as diamagnetic. A superconductor also tries to keep the flux within itself constant when it experiences a magnetic field change. This property is

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A hybrid superconductor magnet bearing system has been developed based on passive magnetic levitation and the flux pinning effect of high-temperature superconductivity. The rationale lies in the unique capability of a high-temperature superconductor (HTS) to enhance system stability passively without power consumption. Characterization experiments have been conducted to understand its dynamic behavior and to estimate the required motor torque for its driving system design.

These experiments show that the hybrid HTS-magnet bearing system has a periodic oscillation of drag torque due mainly to the nonuniform magnetic field density of permanent magnets. Furthermore, such a system also suffers from a small superimposed periodic oscillation introduced by the use of multiple HTS disks rather than a uniform annulus of HTS material. The magnitude of drag torque is velocity independent and very small. These results make this bearing system appealing for high-speed application. Finally, design guidelines for superconducting bearing systems are suggested based on these experimental results.

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In superconductor-magnetic bearing systems, levitation forces are produced mostly by sets of two permanent magnets of the same or opposite polarities. However, there is an inherent instability in the interaction of the two normal permanent magnets. In order to enhance system stability HTS material can be introduced. High-temperature superconductors passively achieve stability by diamagnetism and flux pinning. When a permanent magnet is placed above a diamagnetic body like a superconductor, a levitation force is generated. Therefore, additional levitation force is provided by the interaction between a HTS and a normal permanent magnet even though it is relatively small.

While there are certain advantages of using HTS in magnetic systems, there are some disadvantages. It is observed that a superconductor-magnetic bearing system experiences nonlinear elastic restoring forces and hysteretic drag forces within some ranges of angular position as a consequence of the interaction between the magnet and the HTS [6,7].

In order to further the understanding of this dynamic behavior, characterization experiments have been conducted. This characterization gives information for the design of future superconductor-magnetic bearing systems, such as the elastic restoring force, hysteretic drag force, position and velocity dependencies, and their stiffness, etc. It also determines the motor torque required for the precise control of the bearing system.

III. CHARACTERIZATION EXPERIMENTS

A. Hybrid HTS-Magnet Bearings For Lunar Telescope

In previous work, we have developed a prototype hybrid superconductor magnet bearing system for a lunar telescope azimuth mount [4,5]. The rationale lies in the unique capability of HTS to adapt to the low temperature and vacuum environments in space or on the Moon, and to enhance system stability passively without power consumption. This bearing system is used for these characterization experiments.

The hybrid HTS-magnet bearing system for a lunar telescope (Fig. 1) consists of three parts: inner support tube, outer support structure and rotor [4]. The entire bearing structure is about 1 m tall and its mass is about 7 kg. The bearing assembly can support a load of about 4.5 kg, while its own weight is approximately 6.8 kg. The bearing stiffness is about 10~20 kN/m. The assembled bearing structure makes two hybrid HTS-magnet bearings.

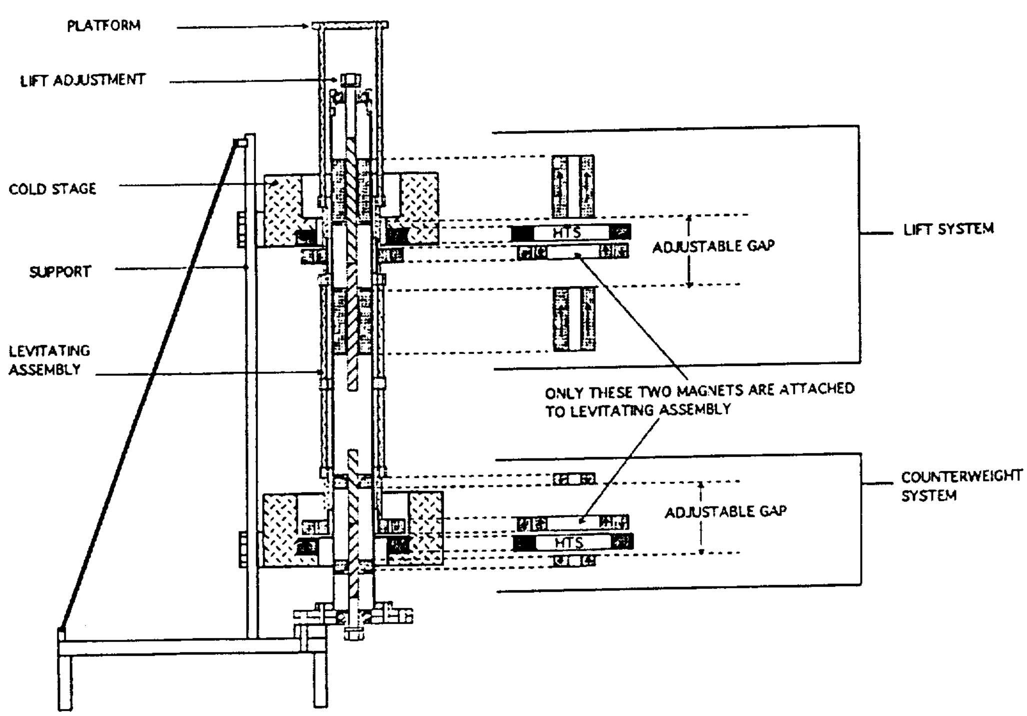

Fig. 1. Schematic of the hybrid HTS-magnet bearings for a lunar telescope

Fig. 1 shows a schematic of the hybrid HTS-magnet bearing system for this telescope. The rotor has two sets of two concentric ring magnets attached to the cylindrical rotating structure at one-quarter of the height from the top and one-sixth of the height from the base. They are assembled by fitting one into the other with opposite polarity and its outer diameter is 10 cm. The inner support tube is located inside the rotor structure and its diameter is approximately 4 cm. The two stator magnets for each bearing are contained within this thin-walled stainless-steel tube. The HTS material is housed within two cold stages which are fixed separately to the outer support structure at one-quarter of the height from the top and one-sixth of the height from the base.

The configuration of the HTS is shown in Fig. 2. Eight HTS disks are located 45 degrees apart around the circle of 7.62 cm. Each HTS is 2.54 cm in diameter and 0.6 cm in height. HTS is made of melt-textured YBaCuO and the permanent magnet is made of NdBFe. The gap size between the HTS and the rotor magnet is 2 mm.

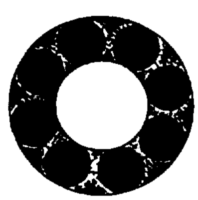

Fig.2. High-temperature superconductor (HTS) disk configuration

B. Experimental Setup and Procedure

An experimental setup for the characterization has been assembled as shown in Fig.3 [8]. The superconductor-magnetic bearing system is securely fixed on the Melles Griot solid aluminum optical breadboard. The platform of the telescope, which is attached on top of the bearing rotor. is coupled to a Himmelstein model MCRT 3L-08T, 10 oz-in (70 mN-m) range, non-contact rotating torque transducer via a Thomas miniature flexible disc coupling, which provides relatively high torsional stiffness along the shaft axis and compliance along all five remaining degrees of freedom. The other shaft of the torquemeter is coupled to the MicroMo planetary gearhead 23/1 (gear ratio of 1526:1) via a Thomas miniature flexible disc coupling. The gearhead is attached to a MicroMo brushless DC servomotor 2444S024BK315, which is attached to a Hewlett Packard HEDS-5500 two channel incremental optical encoder with a resolution of 512 counts-per-revolution with quadrature output.

The torquemeter is connected to a model 61201DL universal strain gauge amplifier and the measured torque is displayed through a model 61201-OZ-IN digital, universal strain gauge amplifier-display. The brushless D.C. servomotor is connected to a low voltage pulse-width-modulation (PWM) amplifier, Western Servo Design BPW-S3-6/10.

For data acquisition and control, a motion control interface card for PC, Precision MicroDynamics model MFIO-3A-ISA-0, is inserted into a PC. This I/O card has a three channel encoder interface and DAC interface within one board and has an open architecture allowing hardware access at the register level. Analog Devices' 12-bit and 600 ksps analog-to-digital converter (ADC) chip, AD7892AN-1, is integrated into the MFIO board for torque transducer analog input.

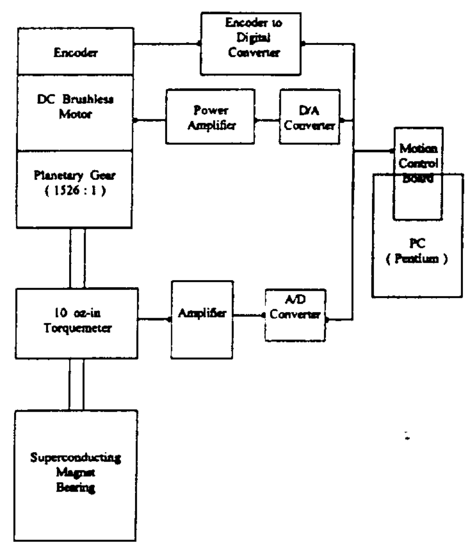

Fig. 3. System configuration for characterization experiments

Mechanical supporting structures for the setup are designed and assembled. Computer codes were written in C++ for measurements.

To obtain constant velocity of the superconducting bearing for its characterization, the drive motor speed was regulated in a proportional-plus-integral (PI) velocity control loop. The PI velocity control law has the form:

$$u(t) = K_v(\dot{\theta}_{des} - \dot{\theta}) + K_i \int (\dot{\theta}_{des} - \dot{\theta})dt, \qquad (1)$$

where $u(t)$ is a control input and $\dot{\theta}$ and $\dot{\theta}_{des}$ represent actual and desired angular velocities, respectively. K_v and K_i are error feedback gains.

The positions of the bearing were measured using an encoder and they were differentiated to get velocity data. A finite-impulse-response (FIR) low-pass-filter was then applied using the MATLAB Signal Processing Toolbox to filter out the noise. The sampling rate was 1 kHz. Drag forces were measured using the torquemeter with a resolution of 0.07 mN-m. The same filter was applied to remove noise from the torque data.

To investigate the velocity dependence of the drag forces, the bearing was rotated without load for three different command velocities: 0.02 rad/sec, 0.2 rad/sec, and 1 rad/sec. The range of test velocity was limited by both friction in the gear with high gear ratio, and motor capacity. The structural dynamics were assumed negligible in the frequency range of measurements. We could also assume that aerodynamic drag and centrifugal force due to mechanical unbalance were negligible at these velocities. To reduce the effect of mechanical unbalance and asymmetry of HTS further, only the HTS of the top bearing module was cooled by liquid nitrogen and used for measurements.

IV. Results and Discussion

Figures 4-6 show the drag torque measured at three different rotational velocities. These results demonstrate that the torques oscillate with periodicity. The data shows that all of these match well with a sinusoidal function having an amplitude of about 1 mN-m. The amplitudes do not increase with rotational velocities. The torque

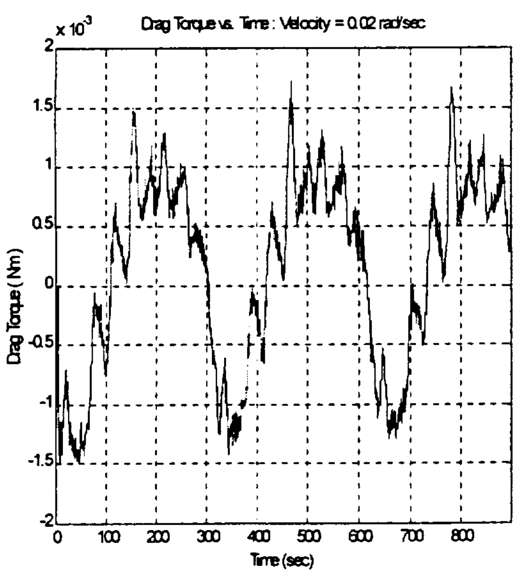

Fig. 4. Drag torque at 0.02 rad/sec

spike seems mainly due to a larger flux jump at higher velocity.

Therefore, it can be said that there is basically no change in the magnitude of drag torque as one changes the rotational speed by more than an order of magnitude.

The oscillation of torque with periodicity seems to be caused by two facts. First, the magnets do not have uniform magnetic field density. Second, the rotor magnets are not perfectly symmetric about the axis of rotation. As a result, they may make a different gap size

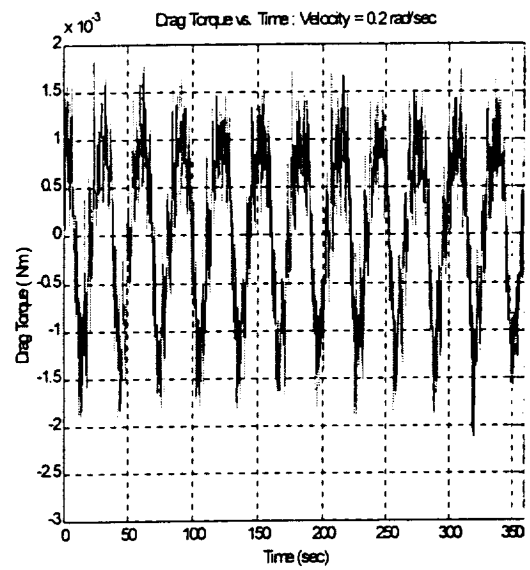

Fig. 5. Drag torque at 0.2 rad/sec

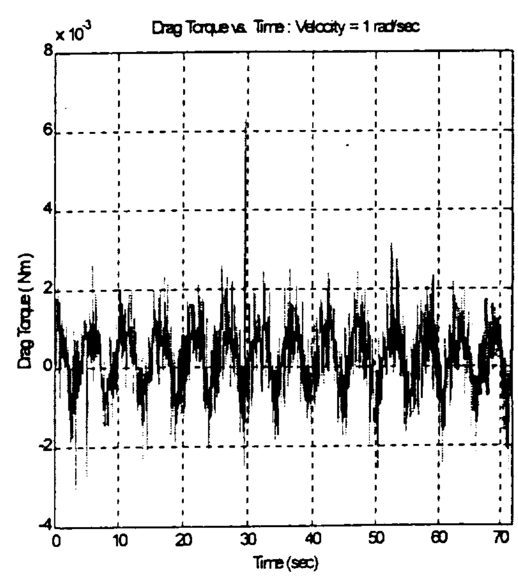

Fig. 6. Drag torque at 1 rad/sec

between the HTS and themselves at a certain angular position while they rotate. Fig. 4 shows eight bumps per cycle superimposed on the sinusoidal function. These oscillations could be identified with elastic restoring forces associated with a slightly uneven distribution of trapped magnetic flux around the ring of superconductor disks. It is caused by the fact that the superconducting ring is not one continuous annulus but instead eight separate disks or pieces as shown in Fig. 2.

It is observed that the drag torque is somewhat dependent on operation conditions such as humidity and temperature. For accurate measurement, the torquemeter needs to be calibrated frequently and the torque offset should be recompensated.

V. Conclusions and Future Work

Characterization experiments show that HTS-magnet bearing system exhibits a periodic oscillation of the drag torque. The magnitude of drag torque is velocity independent and small which makes the bearing appealing for high-speed application. The bearing also has a small superimposed periodic oscillation due to discontinuous distribution of HTS. This oscillation will make its fine control difficult especially at low velocity.

Based on experimental results, a few design guidelines can be suggested. To achieve high system performance, it should be designed using permanent magnets with uniform magnetic field density. It is also recommended that the HTS ring should be made of one piece or annulus. Static and dynamic mechanical balance needs to be secured, including the uniform gap size between HTS and the magnets. For coupling of HTS magnets, it is recommended to use zero magnetic field gradients in the desired direction of motion by using magnets of the same polarity. Likewise, high magnetic field gradients should be used for the undesired direction of motion by adopting magnets of opposite polarity.

Future work involves the study of creep, velocity dependence of hysteresis energy loss, and hysteresis energy loss from magnet asymmetry. Due to hysteresis drag torques, active control may be needed for high system performance. The relationship between rotational velocity and oscillation period needs to be further studied.

HTS magnetic bearing systems have many promising applications. Both industry and space programs can benefit by the development of such a device. A flywheel kinetic energy storage system incorporating superconductor-magnetic bearings can be used for renewable energy storage from fluctuating sources such as the wind. The levitated momentum wheels isolate vibration and reduce noise, thereby exciting the structural dynamics of spacecraft less. Micro-electromechanical systems (MEMS) can also benefit from levitated bearings since wear is the most serious problem due to the high surface-to-volume ratio in the micro domain [9]. The feature of low power dissipation is especially advantageous in space where power budget is tight. Superconductor-magnetic bearing systems are used as momentum wheels, which are actuators for attitude control system of micro-satellites and spacecraft. High-speed rotation with high efficiency results in a high bandwidth attitude control system, which can achieve better disturbance rejection. HTS-magnet bearings can be used as flywheel energy storage in space.

Compared to conventional mechanical bearings, the HTS bearing is superior with regard to having an extremely low bearing loss, but lacks stiffness to support sizable loads and operates only under cryogenic conditions. Thus, it fits naturally in deep space or on the Moon which is a cold vacuum and is away from any significant source of gravity. The reduced gravity on the surface of the Moon makes the weight of the telescope a manageable load for the superconductor magnetic bearing, despite its weak stiffness. Finally, the passive nature of the superconductor-magnetic bearing means that it takes no power source to run it, so long as it is adequately shaded to keep the superconductors cold enough as done with the International Space Station in low Earth orbit. This makes it advantageous over active magnetic bearings when a source of power is scarce. In summary, the superconductor-magnetic bearing is uniquely suited for space applications.

Acknowledgment

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