CRYOCOOLER APPLICATIONS FOR HIGH-TEMPERATURE SUPERCONDUCTOR MAGNETIC BEARINGS*

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DISCLAIMER

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ABSTRACT

The efficiency and stability of rotational magnetic suspension systems are enhanced by the use of high-temperature superconductor (HTS) magnetic bearings. Fundamental aspects of the HTS magnetic bearings and rotational magnetic suspension are presented. HTS cooling can be by liquid cryogen bath immersion or by direct conduction, and thus there are various applications and integration issues for cryocoolers. Among the numerous cryocooler aspects to be considered are installation; operating temperature; losses; and vacuum pumping.

HTS MAGNETIC BEARINGS

Stable Levitation

In its simplest form, a superconducting bearing comprises a permanent magnet levitated in a stable position over a superconductor.[1] A levitation force develops, because of the superconductor's tendency to exclude magnetic flux (the Meissner effect), making them behave like a strong diamagnet. Accordingly, a superconductor with a permanent magnet positioned close above it develops a shielding current, which excludes the flux in such a way that the actual magnet "sees" its mirror image.

More specifically, if a permanent magnet is vertically magnetized with its north pole down, the image will also be vertically magnetized but with the north pole up, exerting a repulsive force on the real magnet. The closer the magnet gets to the superconductor, the stronger the repulsive force; the farther away the magnet moves, the weaker the force. This arrangement can yield a levitation that is stable in the vertical direction.

Horizontal stability is achieved attained by flux pinning. A flux-pinning center is an inclusion, crack, or other crystalline defect in the superconductor. Since the superconducting region surrounding the nonsuperconducting center is strongly inclined to exclude magnetic flux, a flux line through the center tends to become trapped there. When enough flux lines are trapped in this way, a permanent magnet will remain levitated in position, even over a flat surface.

The flux lines between the permanent magnet and the superconductor surface behave rather like mechanical springs with attachments to magnet and superconductor. If the magnet is moved up and down or sideways, it will tend to be pulled by the "springs" back to its equilibrium position.

Bearing Details

Unlike superconducting wire applications, in which the supercurrent must pass from grain to grain along quite a distance, the supercurrent for superconducting bearings needs to circulate only within individual grains. The present material of choice for superconducting bearings that operate at liquid nitrogen temperatures is yttrium-barium-copper-oxide (YBaCuO). Grains of this material can grow to diameters of several centimeters when made by a process called melt-texturing.

In the present state of the art, the upper limit to melt-texturing appears to be about a 10-cm diameter. The levitation force that the superconductor can provide is proportional to its average magnetization, which is proportional to the product of its grain diameter times its current density. The critical current density in these HTS samples is about 40,000 A/cm^2, which together with a diameter of several centimeters, allows levitation pressures between the superconductor and a neodymium-iron-boron permanent magnet to be as high as about 280 kPa.

In practical bearings, the low levitation pressure available in the interaction between permanent magnet and superconductor is often augmented by various hybrid schemes in which interactions between pairs of permanent magnets provide the bulk of the levitation force. These interactions are unstable, but the inclusion of a properly designed HTS component is sufficient to stabilize the complete bearing.

THE BEARING SYSTEM

The bearing system considered is as shown schematically by Figure 1. The system is comprised of the 1) Suspended mass to which is affixed 2) a permanent magnet which is levitated by 3) a HTS magnet which is connected by 4) supports to the 5) vacuum vessel. The 6) rotational axis is taken to be vertical.

The details of the suspended mass vary with the specific applications and may require operational access along the rotational axis. Correspondingly, the support and vacuum vessel details vary with application.

The HTS bearings are cooled to their operating temperature by an external refrigeration source.

For the purposes of quantitative discussions, which follow, of cryocooler integration issues; the following representative HTS bearing parameters will be employed: ID = 10.2 cm (4 in.), OD = 22.9 cm (9 in.), t = 1.27 cm (0.5 in.), and mass = 1450 g. The HTS material is melt textured YBCO.

LIQUID BATH COOLING

The HTS bearings can be cooled by immersion in a cryogenic liquid bath.

Advantages

The advantages of liquid bath cooling include the following:

1) Effective heat transfer by direct contact with the HTS material.

2) Thermal reserve to accommodate upset conditions.

3) Operation with cryocooler recondenser and/or with external bulk liquid cryogen source.

4) Potentially low vibration input.

5) Optional non-metallic bath containment.

6) Optional common refrigeration source for both bearings.

Disadvantages

1) Need for liquid inventory that must be initially developed and then maintained. Associated details include a) level monitoring/control, b) upset response, and c) pressure vessel safety.

2) Need for vacuum leak tight cryogen bath container and associated connections.

Representative System

A representative liquid bath cooling system that incorporates a cryocooler is as shown schematically by Figure 2. The system is comprised of the 1) HTS bearing magnet, 2) a liquid bath reservoir fed by a 3) liquid supply reservoir. All reservoirs and their interconnecting piping are located in the 4) system vacuum enclosure. More than one liquid bath reservoir can be fed by a common liquid supply reservoir.

By locating the supply reservoir above the bearing reservoirs, and piping the bearing reservoir vent gas stream into the supply reservoir gas space; a quasi thermal siphon is possible. For circulation to exist,

$$(\rho_S - \rho_R)g\ell > \Delta P_{loop}$$

where ρ_S = supply column fluid density, ρ_R = return column fluid density, g = acceleration due to gravity, ℓ = fluid head length, and ΔP = pressure drop around loop.

The LN_2 supply system can be operated as an essentially closed system by the incorporation of a cryocooler driven LN_2 condenser. The condensing surface can be located in the gas space of the supply reservoir. Depending on the capacity of the cryocooler and the system losses, the system could operate in the subcooled mode which would allow operation at temperatures less than the normal boiling point of the cryogen employed.

CONDUCTION COOLING

The HTS bearings can be cooled by solid conduction to a refrigeration source.

Advantages

1) No need for HTS bearing cooling liquid inventory and associated operational details.

2) Operation with a cold plate that is cooled by a cryocooler cold head. Cryocooler operation results in stand alone, plug-in operation.

3) Gravity is not a factor in cooling.

Disadvantages

1) Potentially poor heat transfer with the HTS material.

2) Limited thermal reserve to accommodate upset conditions.

3) Potential vibration input.

4) Potential metallic components in the bearing region which could contribute operating losses.

Representative System

A representative solid conduction cooling system that incorporates cryocoolers is a shown schematically by Figure 3. The system is comprised of the 1) HTS bearing which is cooled via 2) a heat transfer connection to the 3) cryocooler cold head. The cold head is mounted to the 4) vacuum enclosure.

CRYOCOOLER SYSTEM REQUIREMENTS

Availability

The HTS bearings will be competing with conventional bearings, either active or passive, that are generally very reliable and only require infrequent maintenance at manufacturer-recommended intervals. For the conventional bearings, unscheduled shut-down for maintenance is rare. The HTS bearings, on the other hand, require cryogenic cooling. The maintenance schedule of the cryocooler should match the parent device's maintenance schedule.

Cooling Capacity

The required cooling capacity of the cryocooler depends on the design of the HTS bearing system and the cooling method employed.

During cooldown from ambient temperature to a nominal operating temperature of 77 K, the total thermal energy to be removed from a single conduction-cooled HTS bearing is on the order of 100×10^3 Joules. If the HTS bearing is liquid-bath cooled and is installed in a representative epoxy fiberglass (G-10) reservoir having mass of 4.1 kg (9.2 lb), an additional 600×10^3 Joules of thermal energy must be removed during cooldown; making the total cooldown energy removal of 700×10^3 Joules per bearing assembly.

The time to cooldown should be compatible with the parent system's requirements.

Transfer Losses

Transfer losses that occur during the delivery of refrigeration from the cryocooler to the bearing substantially contribute to the overall cryogenic load for the cryocooler. These losses would be greatly reduced if an innovative integral design of a cryocooler into the bearing could be developed and implemented with part of the cryocooler system such as the cold head, or the entire unit built into the bearing and its containment.

CRYOCOOLER INTEGRATION ISSUES

Installation

While the cryocooler provides the refrigeration that is necessary for the operation of an HTS magnetic bearing, its installation must complement the functionality of the device that employs the bearings. As such the cryocooler should be compact and have low weight. Its interfaces with the vacuum vessel and the cold head connection point should permit cryocooler maintenance access and provide for straightforward cryocooler changeout.

The axial separation; i.e., gap, between the permanent magnet and the HTS magnet should be minimized as the levitation capacity of the bearing depends strongly on distance between the permanent magnet and the HTS magnet. Thus the thickness of any intermediate members; i.e., liquid bath reservoir walls, etc., associated with bearing's refrigeration should be minimized.

Operating Temperature

A HTS's levitation capacity is a function of the material's operating temperature. Levitation force increases as material temperature decreases. Thus it is important to avoid temperature gradients in the HTS bearing elements due to cryocooler refrigeration coupling that could lead to losses in levitation capacity.

The temperature of the surface of the HTS material that faces the permanent magnet is most important to its levitation performance. This surface is also closest to sources of ambient heating; i.e., temperature gradients, due to incident thermal radiation.

The levitation capacity of the superconductor can be significantly improved by lowering its temperature. For the example YBaCuO, the levitation capacity at 77 K is increased by 13% at 66 K. Such conditions can be achieved with liquid bath cooling with the liquid operating in the subcooled mode; i.e., liquid boiling at subatmospheric pressure, and in the conduction cooled mode by lowering the cold head operating temperatures. The conduction cooling mode appears to be the preferred method to achieve such operation.

Thermal Mass

A reduction in cryocooler output could result in an increase in the temperature of the HTS bearing material which would reduce its levitation capability which could lead to bearing failure. In order to allow adequate time for a safe, controlled shutdown of the parent system; thermal mass can be added to slow the temperature rise of the HTS material. Thermal mass can be in the form of a solid material in contact with the HTS material or reserve liquid cryogen inventory. The inclusion of solid material thermal mass will affect cooldown.

Losses

The direct losses of a superconducting bearing consist of losses in the rotating permanent magnet and losses that appear in the HTS. The latter are more important, because heat deposited in the HTS must be removed at cryogenic temperatures. The losses in the HTS part of the bearing include magnetic hysteresis loss in the HTS itself and thermal losses arising from thermal conduction and radiative heat flux to the cryochamber.

Magnetic friction

Magnetic hysteresis is the dominant loss in the HTS. The HTS experiences a changing magnetic field as the bearing rotates. Part of this changing field is due to inhomogeneities in the permanent magnet. That is, if one measures the magnetic field near the surface of a cylindrical magnet at a fixed radius as a function of circumferential angle, one will measure a large mean value with a small variation that depends on angle. It is this small variation that creates the hysteresis loss in the HTS. Additional magnetic field variation will be experienced by the HTS if the levitated permanent magnet undergoes vertical or radial oscillation or exhibits a whirl amplitude. The drag torque of hysteresis loss is independent of rotational speed, and the thermal power deposited in the HTS is directly proportional to speed.

Eddy current

The same magnetic field variation that causes hysteresis loss in the HTS will cause eddy current losses in any electrically conducting component of the cryochamber. The heat power input in this case is proportional to the square of the rotational speed. The field variation from the rotating magnet may also cause eddy currents in electrically conducting components of the system outside of the cryochamber. If the HTS is composed of an array of components or otherwise has a significant inhomogeneity, the magnetized array will exhibit its own magnetic field variation over the volume of the rotating magnet. If the magnet is electrically conducting, it will experience eddy currents.

Vibration

Vibrations imposed on the HTS bearing system will contribute to the losses of the system. The tolerance to vibration depends on the nature of the specific bearing system. An acceptable level could be on the order of several microns, with 100 μ being generally unacceptable.

Thermal

Sources of thermal losses are support and piping solid conduction, residual gas conduction, and thermal radiation.

Solid conduction can be minimized by conventional cryogenic design measures, and residual gas conduction is negligible due to the bearing's operational vacuum requirement of less than 10^{-6} Torr.

Thermal radiation can be significant due to the high emissivity; i.e., $\varepsilon \approx 1$, of the YBaCuO bearing material which is dull black. The same applies to the case where the bearing is enclosed in an epoxy fiberglass reservoir (G-10 EFG) where $\varepsilon \approx 1$.

Thermal radiation can be controlled by coating the high emissivity surfaces with a low emissivity material such as aluminum or stainless steel. The type and thickness of the material must be carefully considered as a metallic interface between the spinning permanent magnet and the HTS magnet can contribute to the bearing's eddy current losses.

Thermal radiation can also be controlled by the use of multilayered insulation (MLI). As in the case of coatings, the use of MLI can contribute to the bearing's eddy current losses.

For purposes of example, the thermal radiation between 300 K to 77 K has been estimated for the representative bearing system (see section "The Bearing System"). Cold (77 K) surface areas are 588 cm^2 (91 $in.^2$) for conduction cooled (HTS bearing only) and 5600 cm^2 (868 $in.^2$) for liquid bath cooled (reservoir). Cold surface emissivities for coatings are assumed to be 0.05. Warm surface emissivity is assumed to be 0.05 (stainless steel vacuum vessel). For MLI, three layers were assumed with a heat flux of 2 W/m^2.[2] The results of the estimate are given in Table 1.

Table 1. 300 K to 77 K thermal radiation estimates[a]

Cold (77 K) Surface	Cold Surface Treatment	Thermal Radiation [W]
HTS bearing (YBaCuO)	Uncoated	2.55
HTS bearing (YBaCuO)	Reflective coating	0.91
HTS bearing (YBaCuO)	MLI	0.11
Liquid Bath Reservoir (G-10 EFG)	Uncoated	24.3
Liquid Bath Reservoir (G-10 EFG)	Reflective coating	8.70
Liquid Bath Reservoir (G-10 EFG)	MLI	1.12

[a]Per single bearing assembly

Cryocooler efficiency

The cryocooler efficiency contributes to the overall efficiency of the parent system. This is particularly important in cases where the bearing is incorporated into a flywheel energy storage system.

Vacuum Pumping

The cold (≤77 K) surfaces of the HTS bearing assembly can be utilized for the maintenance of the vacuum (≤10^{-6} Torr) required for efficient (low drag) bearing operation. Such a possible installation is as shown in Figure 4. Emissivity control is utilized to reduce the cooling of the permanent magnet which would reduce its levitation capacity. Graded MLI is employed to reduce thermal radiation and control eddy current losses. A getter is employed for vacuum maintenance.

CONCLUSIONS

- The operation of HTS magnetic bearings can be simplified by the use of cryocoolers to provide the necessary refrigeration.

- Cooling of the HTS material can be by immersion in a liquid cryogen bath which is maintained by a cryocooler or can be by conduction cooling by direct connection to the cryocooler cold head.

- Operation of the parent system determines the cryocooler system requirements which include operational availability, cooling capacity, and transfer losses.

- The installation of the cryocooler must complement the functionality of the parent system.

- The operating temperature must be such that adequate and stable levitation is provided by the HTS bearing.

- Thermal mass can be included to allow for a moderation of HTS temperature variations and to allow adequate time for a safe shutdown in the event of cryocooler failure.

- Losses contribute to the overall efficiency of the integrated system. Factors to be considered in the design process include magnetic friction, eddy currents, thermal heat loads, and cryocooler efficiency.

- The cold surfaces of the HTS bearing can assist in the maintenance of the system's operating vacuum.

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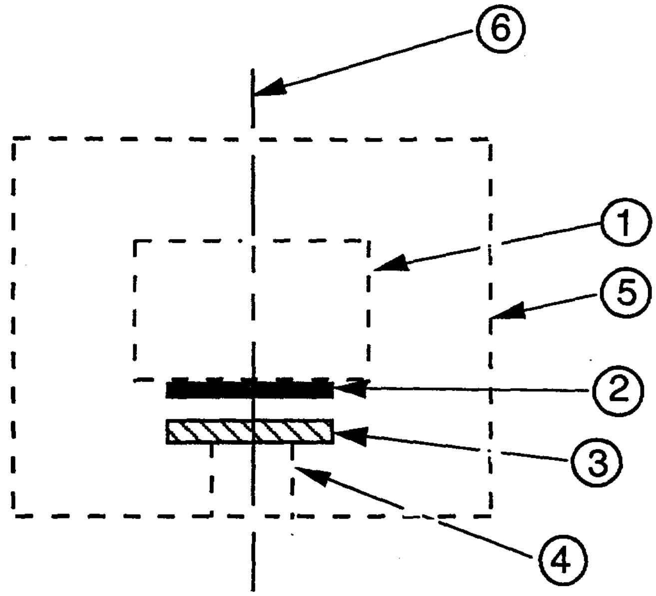

Figure 1. Bearing System Schematic.

1) Suspended mass, 2) permanent magnet, 3) HTS magnet, 4) support, 5) vacuum enclosure, and 6) rotational axis

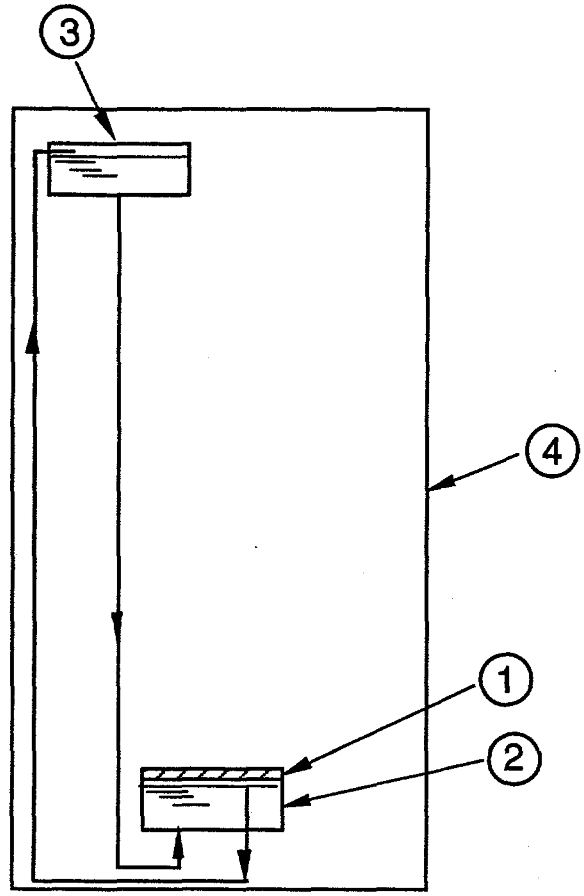

Figure 2. Liquid Bath Cooling System Schematic. 1) HTS magnet, 2) bearing liquid bath reservoir, 3) common liquid supply reservoir, and 4) vacuum enclosure

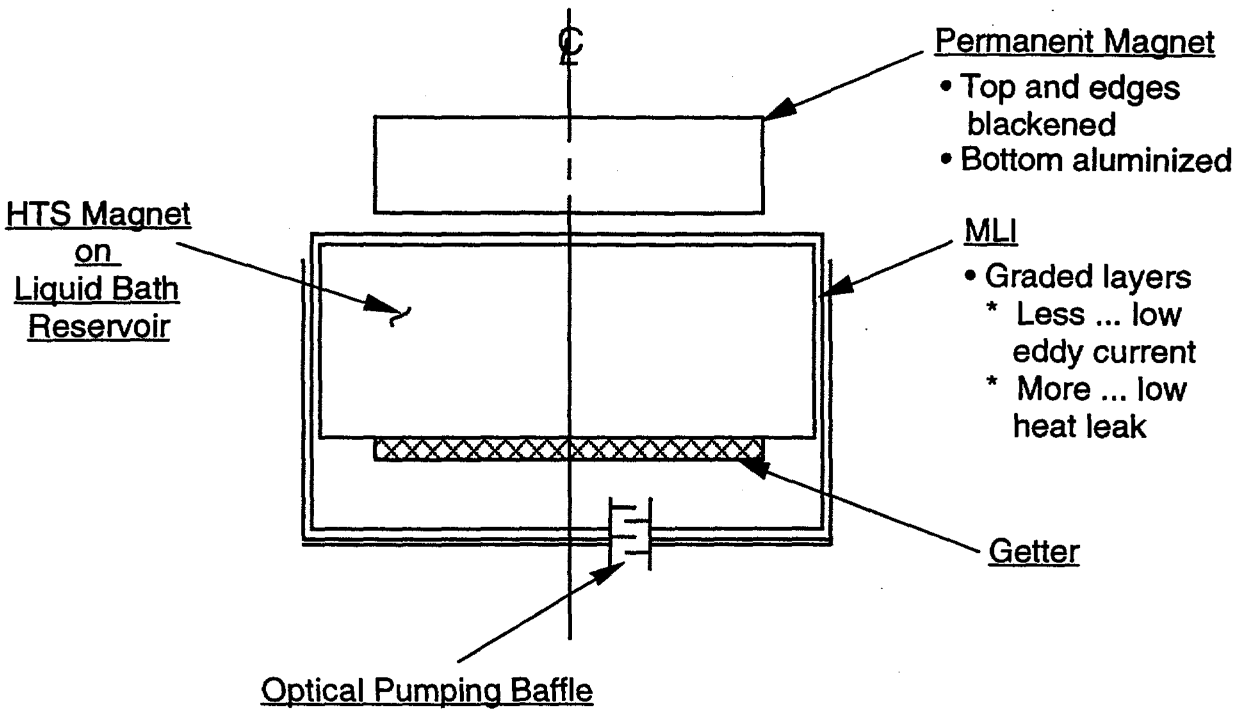

Figure 4. Thermal control and vacuum pumping