# Practical adaptation in bulk superconducting magnetic bearing applications

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(Received 26 November 1991; accepted for publication 3 February 1992)

Lifting capacities greater than 41 N/cm$^2$ (60 psi) at 77 K have been achieved using a combination of permanent magnets and high quality melt-textured $YBa_2Cu_3O_{7-\delta}$ (YBCO). The key concept of this hybrid superconducting magnetic bearing (HSMB) is the use of strong magnetic repulsion and attraction from permanent magnets to support high loads in conjunction with flux pinning in a type II superconductor to counteract instabilities in a system consisting of magnets only. To illustrate this concept, radial and axial forces between magnet/superconductor, magnet/magnet, and magnet/superconductor/magnet, were measured and compared for the thrust and journal bearing configurations on a bearing prototype.

The objectives of developing a more viable high-temperature superconductor (HTS) bearing are to achieve higher stiffness and load lifting capacity while maintaining low rotational dissipation. The origin of the inefficiency in previous systems utilizing active magnetic suspension, such as electrical feedback controls or complex pneumatic gas bearing systems, lies in their continuous energy consumption. With the onset of higher quality materials produced by the texturing processes,[1–3] and with further increases being very promising with neutron and high energy proton irradiation[4–6] of bulk $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO), the corresponding increase in flux pinning can enable oriented samples of YBCO to trap magnetic flux on the same order of magnitude or higher than that of rare-earth permanent magnets.[7,8] Using such high flux trapping samples would raise the levitation and the magnetic stiffness effectively.

Superconductors in their present-day bulk form are good candidates for simple superconducting magnetic bearing (SMB) devices[9–11] such as a levitated magnet over a superconductor cooled in the absence of a magnetic field. However, this simple type of bearing arrangement yields limited levitation and a relatively low magnetic stiffness. This is due to the finite magnetic field from the rotors and the finite critical current density ($J_c$) of the superconducting stator. Yet another problem with SMBs involve gap stabilization over long periods of time, arising from the occurrence of force creep (gap creep)[12,13] under zero field cooled (ZFC) conditions. In contrast, under field cooled (FC) conditions, a negligible static levitation force occurs when no external load is applied in any direction. Hence, FC conditions offer practically no load lifting capacity, which is an obvious disadvantage; but because of this very reason, FC conditions also show no force creep as long as it is not displaced from its original position. Furthermore, a much higher magnetic stiffness for the radial displacement is found under FC as compared to ZFC conditions. In addition, in real application it is impractical to cool the bearing elements (superconductors) before assembling the bearing device (magnetic rotor).

In this letter, a simple approach to improve upon the limitations of the SMBs is presented. This can be achieved by using high quality melt-textured YBCO material placed between the rotor and the stator magnets to overcome the inherent magnet/magnet instability as stated in Earnshaw's theorem.[14] This hybrid superconducting magnetic bearing (HSMB) design allows for greater stiffnesses and maintains a much higher static load-lifting capacity compared to magnet/high-temperature superconductor (HTS) bearings. To demonstrate this, an (HSMB) prototype (Fig. 1) powered by a turbine was constructed, and it exhibits multiaxis stability in a passive levitated state.

This HSMB was fabricated with melt-textured YBCO as stators and NdFeB as rotor permanent magnets with a surface field at the center of a pole face of 0.429 T. In the test model, two melt-textured tubes (1.8 cm length, 1.2 cm ID, 2.5 cm OD) were sealed to the outside of a 5.7 cm long glass tube to form a journal bearing. The thrust HTS bearing member was a melt-textured YBCO disk (2 cm diam, 4.75 mm thick) which was also sealed to the end of the glass tube with the journal bearing. The journal and thrust permanent magnet bearing members were aligned to maximize the magnetic field repulsion strength thereby maximizing the load lifting capacity and stiffness. The rotor shaft (1 cm diam, 10 cm long) contained three simple dipoles, one at the top for an attractive lift, one for the journal, and one for a repulsive thrust at the bottom.

Force measurements were conducted on prototypes simulating each individual HSMB element. A dipole permanent magnet (1.27 cm length, 0.95 cm diam, 0.426 T surface field) used in the rotor shaft was attached to a static force measurement system[15] incorporating an elastic beam with strain gauges. This cantelever beam was fixed to a motorized stage controlled by a computer. A stationary cold stage held fixed on an optical table was filled with liquid nitrogen to cool the superconductor. The data collected were converted into static forces from which the hysteresis of the forces as a function of displacement were deduced.

A series of experiments were performed to correlate the stiffnesses for the magnet/magnet, magnet/HTS, and

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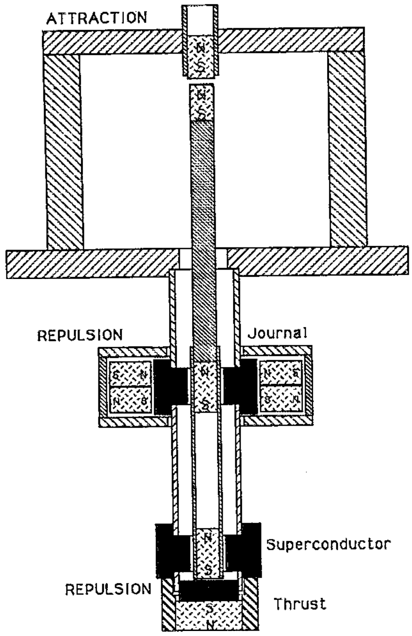


FIG. 1. HSMB bearing cross-section line drawing.

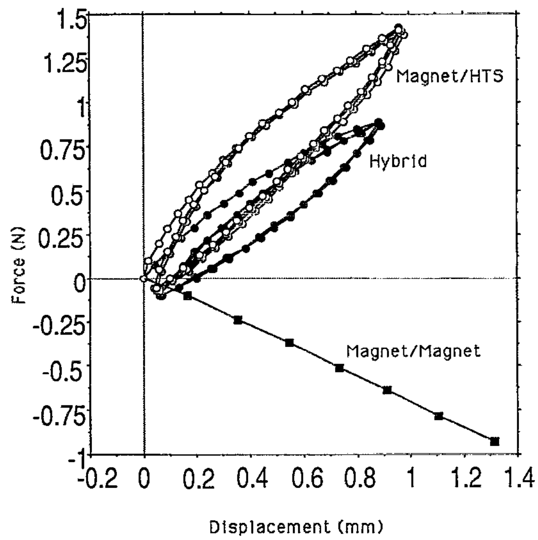


FIG. 2. Axial hysteresis loops—change of force from the initial setup value (different for the three separate cases) as the magnet is translated through the HTS journal stator, as a function of the displacement from the initial point.

the hybrid (magnet/HTS/magnet) configurations. A permanent magnet (1.89 cm diam, 0.73 cm length, 0.316 T surface field) was fixed at the bottom of the apparatus as a stator with polarity repelling the rotor magnet. At 77 K, measurements were taken of the negative shear stiffness and correlated directly to the repulsion force. This same procedure was performed for the attraction magnetic, but the radial stiffness is positive. The rotor magnet in the static setup was held fixed over a superconductor thrust member placed on top of the stator magnet. Radial force hysteresis measurements were conducted for this thrust HSMB with a 6 mm gap between both magnets and compared with the corresponding results for the FC SMB and the negative stiffness of the magnet/magnet component. The journal HSMB was treated in the same manner but in the axial direction.

It is known that the axial force between a magnet and a HTS disk is much smaller under FC conditions than under ZFC conditions. This is no longer a disadvantage for FC conditions, since the central idea is to use magnets to provide the thrust force, with the HTS providing the required stabilization. For example, the FC SMB single bearing element provided practically zero lifting force, while the HSMB provided 9.32 N/cm$^2$ static axial thrust with a magnet to magnet gap distance of 6 mm. Since forces required for stabilization purposes can be expected to be smaller than that of the main thrust, this translates into an advantage for the FC case. This is further supported by the measurements of the retaining force against a displacement in the radial direction. The stiffness that comes from FC conditions is larger, and so is the maximum force that can be sustained before it yields.

Since it would have to supply the required thrust using additional magnets, the next question concerns whether the presence of this extra magnet would annul these advantages of higher stability. To investigate this, first the magnet/magnet interaction was measured for negative and positive forces versus radial displacements. We then measured the force versus displacements with HTS components in between the magnets, and also with the HTS components but without the stator magnet. The experiments without the stator magnet were performed to compare the stabilities that the HTS/rotor magnet combination can provide, both in the presence and in the absence of an additional magnetic field due to the stator, anticipating that it might be more advantageous to provide HTS/magnet stabilization and magnet/magnet thrust force at separated locations. The resulting force hysteresis loops are shown in Figs. 2 and 3. From the force hysteresis loops for the HSMB configurations, it has been definitely shown that the HTS material placed between the magnets is sufficient to confer stability onto the otherwise unstable magnet/magnet system. The effects of the stator magnet are not apparent until displacements as large as a significant fraction of a millimeter from the original position is reached in the starting FC region. Also, in this case, there is no instability to be overcome in the axial direction in the thrust configuration, and similarly for the radial direction in the journal configurations. The measured stiffnesses in the direction of stability are shown in Table I.

In contrast, a comparison of the data in Figs. 2 and 3 shows that the effects from the stator magnet are much more conspicuous in the journal and thrust configurations. The stator magnets are not intended to create an extra thrust, in the journal. They are added to exchange some axial stability for radial stability. With the polarities as we have implemented them, shown in Fig. 1, the axial stiffness is suppressed from the FC HTS case, while the radial stiffness is strengthened, in parallel with the behavior of the corresponding stiffnesses with the same stator magnet configuration in the absence of the HTS (i.e., axially unstable,

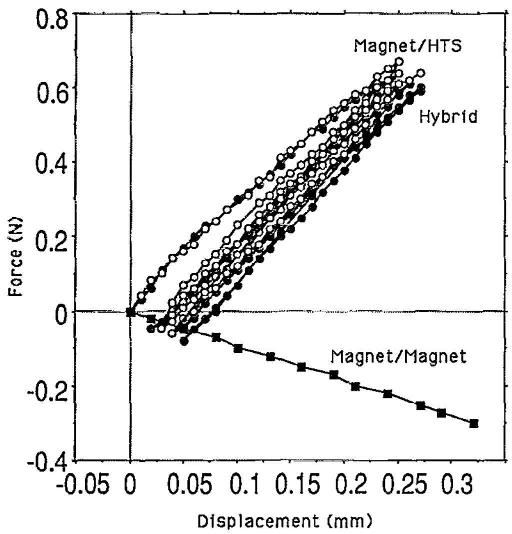


FIG. 3. Radial hysteresis loops—change of force from the initial setup value (different for the three separate cases) as the magnet is displaced across the HTS thrust member, as a function of the displacement from the initial point near the center.

radially stable). In the case of the thrust configuration the hysteresis is unchanged from each configuration and therefore we can conclude that the radial instability from the stator magnet is not affecting the capability of the HTS to pin the magnetic flux and provide stability.

Overall, this HSMB prototype can support a thrust of 41 N/cm$^2$ or 60 psi, normalized to the cross section of the shaft. Of these, about one third comes from the repulsion between the two magnets in the thrust bearing at the bottom, while the remaining two thirds come from the attraction between the two magnets at the top. The bottom thrust bearing has a net radial instability, while the top thrust bearing has a net axial instability. Since these two instabilities stem from forces acting on different ends of the shaft, they would combine to produce a tilt instability even if they appear to cancel each other out. This is just another instance illustrating Earnshaw's theorem. With the HTS fixture, the journal bearing in the middle functions to stabilize against the axial instability of the top bearing, while the HTS component of the thrust bearing at the bottom functions to stabilize against the radial instability from the repelling magnets located in its vicinity. Further refinement of the balance between axial and radial instabilities can be made by adjusting the stator magnets in the journal bearing. When assembled, the overall stiffness of the bearing would be several N/mm, variously distributed among the three bearing components.

In conclusion, it has been shown that the HSMB allows for the thrust to be increased over that which can be expected by ZFC-SMBs. In general, the stiffness of the magnet/HTS/magnet configurations is not exactly a simple superposition of the stiffnesses from the magnet/HTS and the magnet/magnet configurations, but is not very far off in some cases. The thrust that can be achieved is similar to magnet/magnet systems with the same magnet/magnet gap distance. Thus, higher thrusts can be attained if the gap is decreased, but then the thickness of the intervening HTS stabilizer would have to be decreased accordingly or the HTS could be placed in another position with additional magnets. As a result, the radial stability would be compromised. An optimum placement and HTS thickness would have to be determined according to its $J_c$.

TABLE I. Comparison of the axial thrust forces and the measured stiffnesses in the directions of stability between the journal bearing configuration and the thrust bearing configuration.

| | Journal (radial-N/mm) | Thrust (axial-N/mm) | Thrust force (axial-N) |
|---|---|---|---|
| Magnet/HTS | 0.68 | 3.97 | 0.0 |
| Magnet/HTS/magnet | 2.00 | 4.76 | 8.8 |
| Magnet/magnet | 0.218 | 0.79 | 8.8 |

The stabilizing action of the HTS takes place within a certain penetration depth, which is of the order of several millimeters. We believe that if the size of the bearing is scaled up to sizes larger than the penetration depth, the stabilizing action would scale as the magnet/HTS effective interface area, whereas if the bearing is scaled down to sizes smaller than the penetration depth, the stabilizing action would scale as the volume of the HTS component.

This work is supported in part by DARPA Grant No. MDA972-88-G002 and the state of Texas.

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