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# Hybrid Superconducting Magnetic Bearing (HSMB) For High Load Devices

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## SUMMARY

Lifting capacities greater than 41 N/cm$^2$ (60 psi) at 77 K have been achieved with a new type of levitation (hybrid) using a combination of permanent magnets and high quality melt-textured $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO). The key concept of the hybrid superconducting magnetic bearing (HSMB) is the use of strong magnetic repulsion and attraction from permanent magnets for high levitation or suspension forces in conjunction with a superconductor's flux pinning characteristics to counteract the inherent 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 bearing configurations.

## INTRODUCTION

The objectives of developing a more viable high temperature superconductor (HTS) bearing are to achieve higher stiffness and higher load lifting capacity while maintaining high vibration damping and low rotational dissipation at a temperature of 77 K. The origin of the inefficiency in previous systems utilizing active magnetic suspension, such as electrical feed back controls or complex pneumatic gas bearing systems, lies in their continuous energy consumption. Superconductors in their present-day bulk form are good candidates for simple superconducting magnetic bearing (SMB) devices [1, 2, 3] such as a levitated magnet over a disk of YBCO. However, this simple type of bearing arrangement yields limited levitation, limited suspension, and low magnetic stiffness. This is due to the finite rotor magnetic field and the finite Jc of the superconducting stator. In view of the fact that zero field cooling (ZFC) results in force creep (gap creep) [4] and low radial stiffness for such magnetic bearings, field cooled conditions (FC) should be addressed. In addition, it is impractical to cool the bearing elements (superconductors) before assembling the bearing device (magnetic rotor). Under FC conditions, a negligible static levitation force occurs when no external load is applied in any direction. In contrast, a much higher magnetic stiffness for radial displacement is found in FC as compared to ZFC conditions.

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In this report, a simple approach to improve upon the limitations of the SMBs is presented. Higher levitation, suspension, and stiffness forces are needed to implement SMBs into a wider range of applications. This is achievable in a passive magnetic bearing system composed of strong permanent magnets with a design that alleviates the inherent instability as stated in Earnshaw's theorem [5]. The HSMB design overcomes the magnet/magnet instability by using high quality continuously processed melt-textured YBCO material [6] placed between the rotor and stator magnets. This design allows for greater stiffness values and maintains a much higher static load-lifting capacity compared to magnet/superconductor bearings.

## ABBREVIATIONS

| | |
|---|---|
| HTS | high temperature superconductor |
| FC | field cooled |
| ZFC | zero field cooled |
| SMB | superconducting magnetic bearing |
| HSMB | hybrid superconducting magnetic bearing |
| $T_c$ | critical temperature |
| $J_c$ | critical current density |
| YBCO | $Y_1Ba_2Cu_3O_{7-\delta}$ |

## EXPERIMENTAL

A dipole permanent magnet (1.27 cm length, 0.95 cm diameter, 0.426 T surface field) used in a rotor was attached to a static force measurement system [7] incorporating an elastic beam with strain gauges. This cantilever beam was fixed to a motorized stage controlled by a computer. A stationary cold stage held fixed on an optical table was used with liquid nitrogen (77K) to cool the superconductor and, when needed, an opposing permanent magnet. The collected data was converted into static forces and force hystereses versus displacement, for both radial and axial movement with the thrust bearing configuration.

For comparison between ZFC and FC conditions, the axial force creep and the radial stiffness between the rotor magnet and a YBCO disk (0.47 cm thick, 2.23 mm diameter) was measured and the results are displayed in Figs. 1 and 2, respectively.

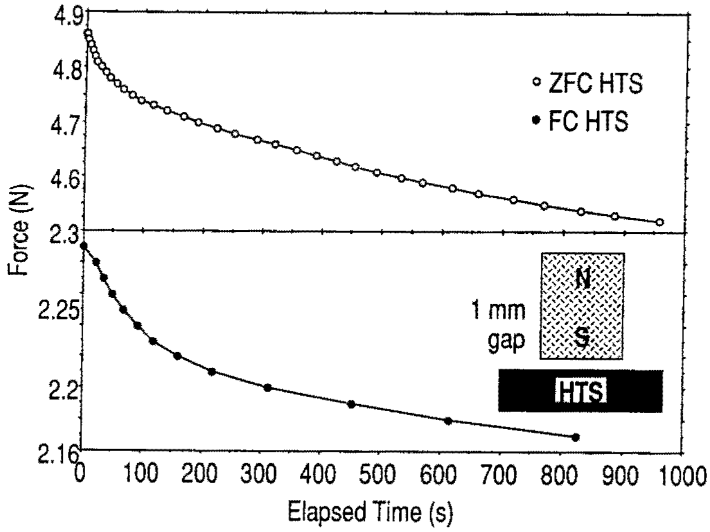

Fig. 1 Force creep - force between magnet and HTS as a function of time under ZFC and FC conditions.

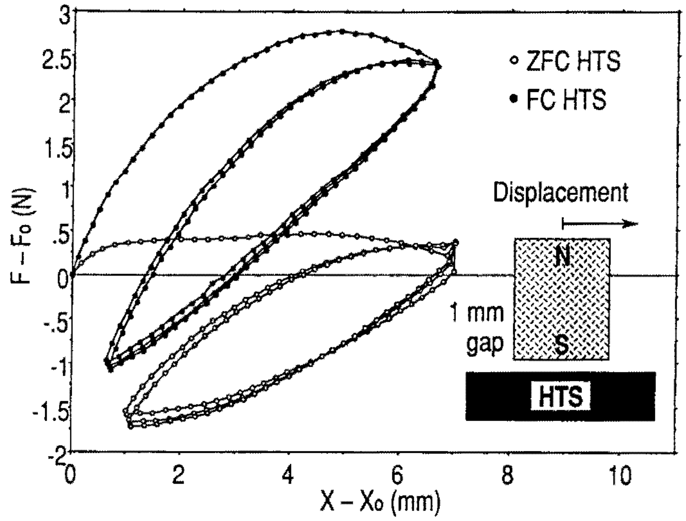

Fig. 2 Radial hysteresis loops - change of force from the initial setup value (different for FC and ZFC cases) as magnet is displaced across an HTS disk, as a function of the displacement from the initial point.

Radial and axial force hysteresis measurements were also taken from the same YBCO disk starting at a fixed distance of 0.25 mm from the surface of the rotor magnet. These results are shown in Figs. 3-5.

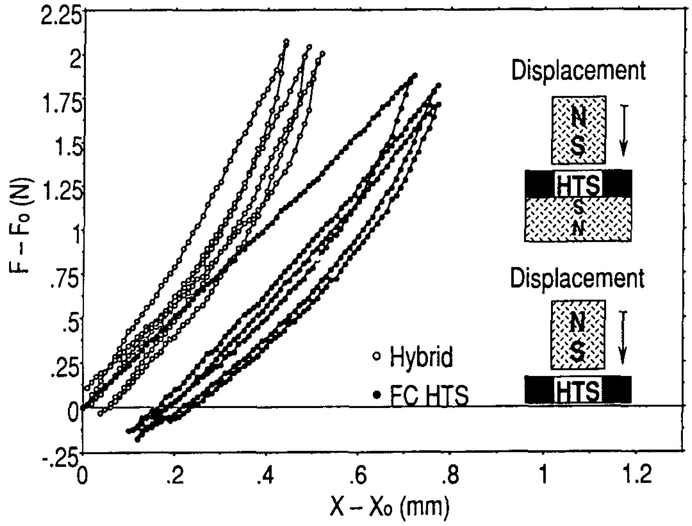

Fig. 3 Axial hysteresis loops - change of force from the initial setup value (different for FC HTS and hybrid cases) as the magnet is pressed onto the HTS disk, as a function of the displacement from the initial point.

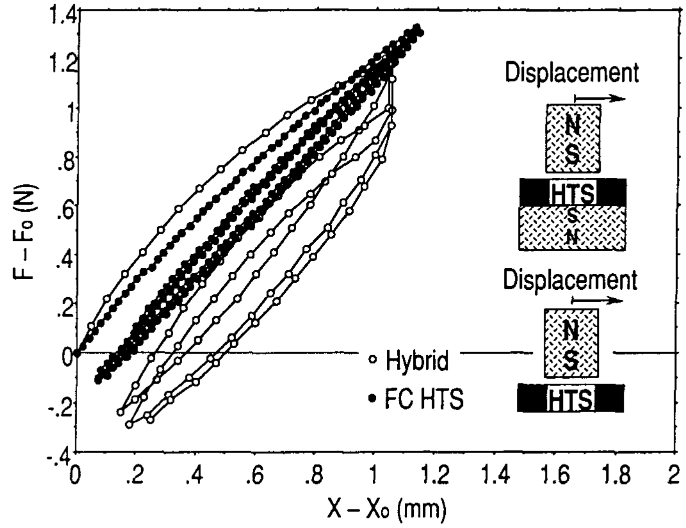

Fig. 4 Radial hysteresis loops - change of force from the initial setup value (different for FC HTS and hybrid cases) as the magnet is displaced across the HTS disk, as a function of the displacement from the initial point near the center.

A permanent magnet (0.95 cm diameter, 1.27 cm length, 0.416 T surface field) was fixed at the bottom of the apparatus as a stator with polarity attracting the rotor magnet. At 77 K, measurements (Fig. 6) were taken of the negative shear stiffness (N/mm) and correlated directly to the repulsion force.

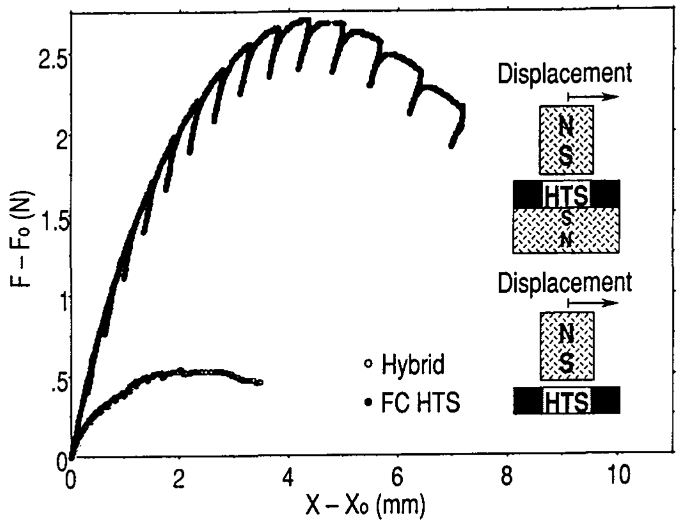

Fig. 5 Radial force versus displacement with minor hysteresis loops - change of force from the initial setup value (different for FC HTS and hybrid cases) as the magnet is displaced across the HTS disk, as a function of the displacement from the initial point near the center.

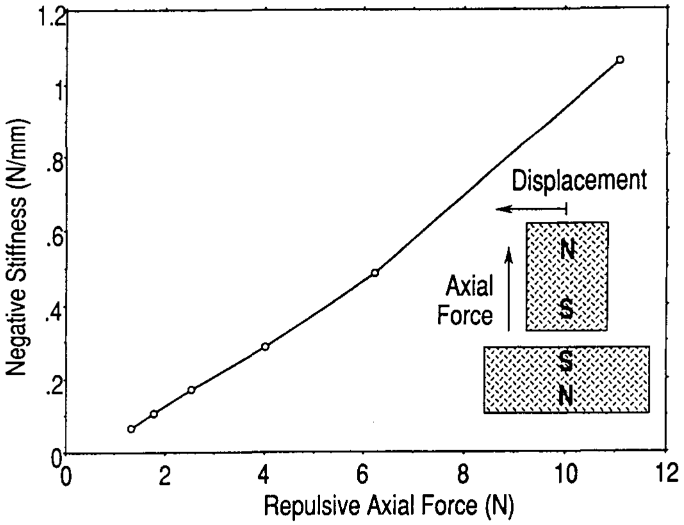

Fig. 6 Stability versus thrust for the stator magnet - the negative stiffness in the radial direction is used as a measure of the instability that has to be overcome if the stator magnet is to provide a given amount of thrust.

Then the rotor magnet was held fixed over a superconductor placed on top of the stator magnet to form a prototype HSMB (magnet / superconductor / magnet) non-rotating setup. Radial and axial force hysteresis measurements were made for this HSMB setup with a 6 mm gap between both magnets and compared with the corresponding results for the FC SMB in Figs. 3-5.

## RESULTS AND DISCUSSION

It is known that the force between a magnet and an HTS disk is much smaller under FC conditions than under ZFC conditions. This is no longer a disadvantage for FC conditions, since our central idea is to use magnets to provide the thrust force, with the HTS providing the required stabilization. For example, our FC SMB provided practically zero lifting force, while the HSMB can provide up to 8.88 N. What we have shown in Fig. 1 is that the force creep under similar load is almost the same for both ZFC and FC conditions. The time scale in which the creep occurs is also similar. In 10 minutes, the magnet/HTS force decreased by 5.3% of its initial value for ZFC conditions, whereas, the decrease was only 4.8% for FC conditions. 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 our measurements of the retaining force against a displacement in the radial direction, as shown in Fig. 2. The stiffness that comes from FC conditions is bigger, and so is the maximum force that can be sustained before it yields.

Since we 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, we have put a magnet below the HTS disk and measured changes of the forces as the rotor magnet above the HTS disk is displaced in the axial and radial directions. The negative stiffness (instability) in the radial direction due to this additional stator magnet is plotted as a function of the thrust that it can provide at various gap distances in Fig. 6. This instability is the inherent instability if we used the magnets only. This is to be overcome by placing the HTS disk in between the two magnets. We have definitely shown that this can be accomplished in Figs. 4 and 5. The effects of the stator magnet are not apparent until displacements as large as a significant fraction of a millimeter from the original position are reached. Although there is no instability to be overcome in the axial direction, we have also included measurements in this direction in Fig. 6, to show the final stiffness that can be achieved in the magnet/superconductor/magnet system. This axial stiffness is similar to that of the magnet/magnet system with the same gap distance between magnets, but is definitely inferior to the magnet/magnet system that has the same gap as the top magnet/superconductor pair in our hybrid system.

In conclusion, we have shown that the HSMB allows us to increase the thrust over that which can be provided by SMBs. The stiffness that can be achieved is similar to magnet/magnet systems with the same magnet/magnet gap distance. Thus, higher stiffnesses can be attained if we decrease this gap, but then the thickness of the intervening HTS disk would be decreased accordingly. The radial stability would be compromised. An optimum HTS thickness would have to be determined.

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