PROGRESS IN SUPERCONDUCTING MAGNETIC BEARINGS

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ABSTRACT

We report on several developments that impact the application of high temperature superconducting materials such as YBCO or BSSCO to passive magnetic bearings for rotary machine elements. Progress has continued to be achieved in the goal of increasing both load and stiffness capabilities. There are efforts in both the US and Japan to levitate large rotors for energy storage devices. At Cornell University, experiments have been carried out on using a wire wound superconducting coil and discrete bulk YBCO superconducting elements to produce pressures in the 100 N/cm2 range and magnetic stiffness in the 100,000 N/m range. These experiments were performed at temperatures of 10° - 30° K. The peak magnetic field produced by the coil was around 2 T. These experiments demonstrate that superconducting bearings need not be limited by the fields of rare earth magnets. The potential for using thin film superconductors is also being explored. Thin films have a much higher critical current density and so offer the potential for generating magnetic forces with a fraction of the material of bulk superconductors and less cryo-cooling requirements.

INTRODUCTION

Industrial acceptability of active magnetic bearings has taken 15-20 years of development. Passive superconducting magnetic bearings (SMB) have had only seven years of development since the discovery of high temperature superconductors such as Ytrium-barium-copper-oxide (YBCO). So it is not surprising that this new class of magnetic bearings has not yet gained industrial acceptance as a bearing concept. However, progress in these seven years has been quite dramatic, in spite of intermittant research funding. (See [1] for a review.) Many prototype SMBs have been built and tested ranging in size from 10 gm rotors, spinning at 500,000 RPM to 1-10 kgm rotors spinning at 5000-30,000 RPM. In both the U.S. and Japan, projects are now underway to build energy storage flywheels supported by passive superconducting bearings.

The main advantage of superconducting bearings are their simplicity and inherent stability in contrast to conventional active magnetic bearings. This advantage is offset by the need for a cryogenic environment. However, we may expect continued progress in the discovery of even higher temperature superconductors in the future (See Table 1). And for stationary applications or cryogenic environments, this need is not a severe design penalty. For example, cyocooler and cryopump bearings would be prime application targets for this new technology. However, stationary flywheels, machine tool spindles, high speed textile spindles and optical scanning devices would also be potential applications.

Another percieved disadvantage of superconducting bearings are their low magnetic stiffness. This however has not been limited by the superconductor as much as the magnetic field source. At the present time, permanent magnets have been used as field sources in prototype bearings with maximum fields of 0.5 T. However recent research at Cornell University and the University of Houston point the way toward higher fields and higher magnetic stiffness for these passive bearings. At Cornell we have done experiments on a concept called a "Super-super

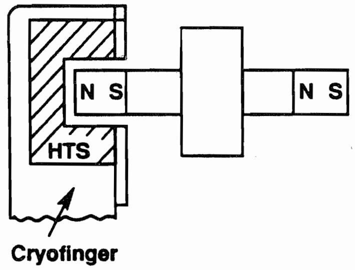

FIGURE 1a.
Monolithic superconducting bearing

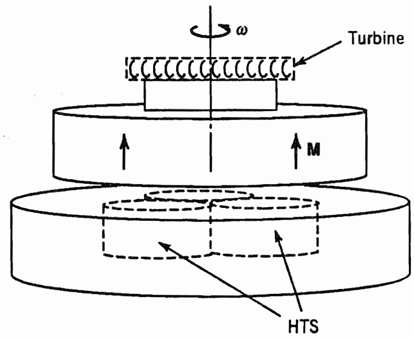

FIGURE 1b.
Discrete Superconducting Bearing elements

magnetic bearing" using a wire wound superconducting coil and a bulk YBCO superconducter [2,3]. The wire wound coil was able to generate a 2 T magnetic field and the interaction of the two superconductors was able to produce a stiffness on the order of 10^5 N/m, which is in the range of active bearings. At Houston, Weinstein and colleagues [4] have produced superconducting permanent magnets which can retain a field of 4-7 T. Such magnets, in combination with bulk superconductors, should be able to produce very high magnetic siffness.

MATERIALS AND CONFIGURATIONS

A magnetic bearing requires a field source and field shaping elements. The typical SMB uses rare-earth permanent magnets as a field source and high temperature superconducting materials as a field shaping element. (Figure 1a) At this time, the most popular material is YBCO with a critical temperature of around 95°K. As shown in Table1 however, new cuprate materials are being developed with higher critical temperatures. One promising material is the Bismuth cuprate BSCCO which is being developed into wire for coil wound magnets. For SMB, a wire wound coil operating in a persistent current mode could provide the rotor based field source with a stationary bulk superconductor as the field shaping system.

YBCO SMB have been used in both radial and thrust bearing configurations. The superconductor element can be used in a monolithic shape enclosing the rotor magnet or can be used as discrete elements. (See Figure 1.) The former design solution is suitable for small rotors. The importance of the discrete element SMB is the fact that the superconductor elements do not have to be fabricated to the size of the levitated mass. Typical sizes for YBCO elements are 1-4 cm diameter or square by 0.5 - 1 cm thick. Experiments at Cornell have shown that approximately 5 mm thickness of the superconductor is needed to obtain the maximum force effect. However with thin or thick film superconductors, one may be able to get large magnetic pressures suitable for levitation using 1-10 micron thick superconductors. This would significantly decrease the cryogenic load on the design.

High-Temperature Superconductors
Critical Temperature °K

La-Ba-Cu-O	35-40 *
Y-Ba-Cu-O	95
Bi-Sr-Ca-Cu-O	85-110 *
Tl-Ba-Ca-Cu-O	108-125 *
Hg-Ba-Ca-Cu-O	133

*Depends on particular crystal structure

TABLE 1

BEARING PRESSURE AND STIFFNESS

The first SMB prototypes in 1988-89 exhibited low magnetic pressures (1 N/cm^2), and low magnetic stiffness (10^3 N/m) [5]. This was due to two effects, low critical currents in the superconductors and low field sources. In the last few years however, dramatic improvements have been made in the critical currents of YBCO using a melt-quench process developed at various laboratories (Bell Labs, ISTEC-Tokyo, Catholic Univ.of America and Univ. of Houston). With 0.5 T permanent magnets, bearing pressures in the range of 10-20 N/cm^2 can be achieved with proper field shaping design. In one technique developed at Univ. of Houston, quadrapole field sources were shown to significantly improve the magnetic stiffness.

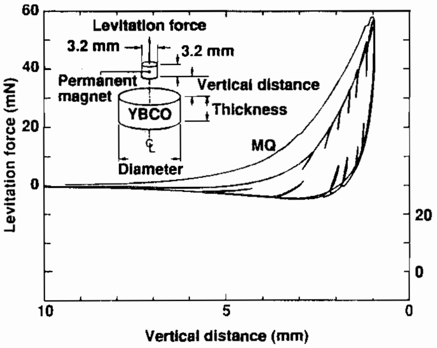

FIGURE 2. Levitation Force -- Displacement for Melt-Quenched YBCO..

One of the techniques to characterize SMB materials is to measure both the levitation force and the magnetic stiffness and to plot them on the same graph. A typical test is shown in Figure 2, and the levitation force versus magnetic stiffness relation is shown in Figure 3. The correlation of force and stiffness merely reflects the fact that both depend on the magnetic field and the field gradient. The striking fact about this relation is that for most good bulk YBCO melt-quench materials this relation is similar. Two exceptions are evident however. If the field source is significantly raised as in a "Super-super bearing", then much higher stiffnesses can be achieved. The other case is thin films where the critical current is significantly higher than bulk materials. (J = 10^4 A/cm^2 for bulk, and J = 10^6 A/cm^2 for thin film superconductors)

SUPER-SUPER BEARINGS

There are several concepts for using superconductors for both field source and field shaping. One concept would use wire wound coils on both the rotor and the stator. This design however may have stability problems of the Earnshaw type if one does not operate one or both coils in the persistent mode. Also one does not have the flux pinning mechanism of a bulk superconductor for added stiffness. The second type of "Super-super bearing" would use a wire wound superconducting coil made out of BSCCO wire as the field source and a bulk superconductor as a field shapping and trapping element. Stability could be obtained without operation in the persistent current mode, but it might be desirable if the coil is on the moving levitated mass. A third type of "Super-super bearing" would use superconducting permanent magnets as a field source and uncharged bulk superconductors as field shaping elements.

Experiments on the second concept have been performed at Cornell University [3]. Two different source coils were used. Since long lengths of BSCCO wire were not available, both Niobium-titanium and Niobium-tin wire were used. These materials were made by the IGC Corp in the USA. To test the proof of principle, the Niobium based coils were run near liquid Helium temperatures while a heater was used to test the levitation forces on the YBCO bulk superconductors at higher temperatures. The coils were run in a constant current mode using a high current power supply(0-200A). Samples were obtained from both ISTEC in Tokyo and Catholic University in Washington D.C.

Results from these tests are shown in Figure 4. The levitation force versus magnetic stiffness relation shows values of the stiffness in the range 10^5 N/m when the peak magnetic field reached 2 T. The comparison of measured and calculated forces was very good. The calculation was based on a near Meissner flux exclusion assumption. It appears to be a paradox that type II YBCO superconductors with high critical currents appear to behave as type I materials when operated in the zero field cooled regime. Also in the range of 30°K, melt quenched YBCO seems to show little of the hysteretic behavior in the force- distance relation.

RESEARCH PROBLEMS

While the future looks bright for superconducting magnetic bearings, there remain important problems to understand in this new technology. Three of these are

hysteresis, force creep and dynamics. Hysteresis effects have been described above. It appears to have both advantages and disadvantages. One advantage is the energy dissipation mechanism that hysteresis provides which could be useful for damping especially in cryogenic devices such as cryopumps. The second advantage is the suspension levitation force that is

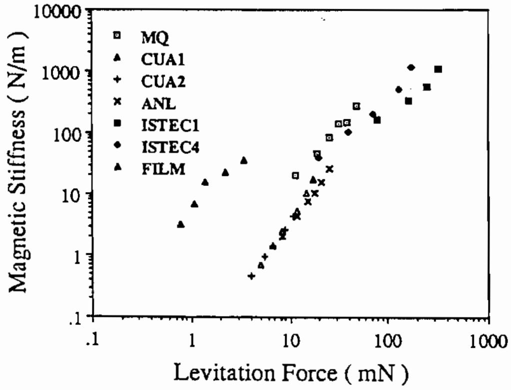

FIGURE 3. Levitation Force vs Magnetic Stiffness for YBCO

sure to be useful for some applications. However the hysteresis also means some uncertainty in the levitation height unless one knows the precise loading history. We also know from force measurements at low temperatures that this hysteresis decreases significantly at low temperatures or at high critical currents. Thus there remains materials processing research to be done to see if one can design in or out the desired amount of hysteresis.

As for force creep, measurements at Cornell and elsewhere have shown a 5-8% drop in levitation force and height in the few minutes after the source magnet is lowered near the superconductor. This force creep is similar to flux creep and appears to follow a logarithmic relation where the next 5% drop occurs over a much longer time scale. These experiments were run on melt quenched YBCO. However reports from researchers in Russia apparantly using sintered YBCO, have reported larger ammounts of force creep. Experiments at Cornell on force creep in thin films also show a large drop in the levitation force or levitation height over the course of ten minutes [6]. Whereas the problem seems to be less for the melt quenched materials, nonetheless further research on force creep would seem prudent if this technology is to move toward application.

The third area for further research in SMB is dynamics, especially the nonlinear and stability aspects of levitated rotors. Two of the primary nonlinearities are the force-displacement relation and hysteresis effects. The latter will certainly translate into significant nonlinear damping. Nolinearities mean that input disturbances at a given frequency, can show up in the dynamics as subharmonics, harmonics, quasi-periodic motions and even chaotic behavior. We certainly do not want to give the impression that superconducting magnetic bearing dynamics are always unpredictable. On the contrary, in the many experiments run at Cornell in the last seven years with small and large rotors, we have generally seen steady rotary behavior. However under vibratory excitation, we have seen some unusual dynamics. An example of this is shown in Figure 5 based on experiments run by sinusiodally vibrating the superconductor under a permanent magnet supported by a flexible cantilevered force sensor [7]. The data in Figure 5 shows the vibration amplitude and frequency regimes where unusual motions of the magnet were observed including subharmonics, quasiperiodicity and chaotic dynamics. Very little research of this kind has been done and almost none on a freely levitated rotor. Some unusual dynamics has been reported on a 2.4 kgm rotor supported by YBCO bearings by ISTEC and NSK Bearings in Japan but the cause was not identified. [8]

CONCLUSION

With the history of active magnetic bearings as a guide and the progress made to date in superconducting magnetic bearings, one might expect applications of SMB to emerge in the next 3-5 years. Also the emergence of "Super-super bearing" concepts using either BSCCO wire coils or superconducting permanent magnets as field sources will likely expand potential applications into the high load and stiffness regime. This also means that SMB will likely challenge the active magnetic bearing industry in 5-10 years in certain application areas. It is hoped that this technical competition will accelerate the pace of magnetic bearing development and engineering acceptance in the next decades.

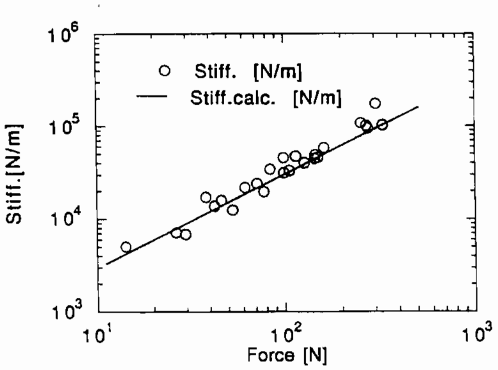

FIGURE 4. Levitation Force Vs Magnetic Stiffness for a Super-Super YBCO Bearing.

REFERENCES

1. F. C. Moon, Superconducting Levitation: Applications to Bearings and Transportation, J. Wiley & Sons, New York, 1994

2. Golkowski, Cz and Moon, F.C., "Levitation Forces in Bulk YBCO in a High Magnetic Field and Low Temperatures", Cornell University Report, 1994.

3. F. C. Moon, C. Golkowski, D. Kupperman, "Superconducting Bearings for High load Applications" Applied Superconductivity **1** (7-9),1175-1174,1993.

4. Weinstein, R. Chen, I. G., Liu, J., Narayanan, R., Ren, Y.R., Xu, J., Obot, V., and Wu, J., "Materials Characterization and Applications for High-T_C Superconducting Permanent Magnets", in Proceedings of the Third World Congress on Superconductivity, Munich, 1992.

5. Moon, F.C., Yanoviak, M.M., and Ware, R., "Hysteretic Levitgation Forces in Superconducting Ceramics," Appl. Phys. Lett. **52**, 1534-1536, 1988.

6. T. Hikihara, F.C.Moon, "Chaotic Levitated Motion of a Magnet Supported by a Superconductor" Superconducting Bearing Laboratory Report, Cornell University, January 1994.

7. P. Schonhuber, F.C. Moon, " Levitation Forces, Stiffness and Force Creep in YBCO Thin Film Superconductors" Superconducting Bearing Laboratory Report, Cornell University, February 1994.

8. Takaichi, H., Murakami, M., Kondoh, A., Koshizuka, N., Tanaka, S., Fukuyama, H., Seki, K., Takizawa, T., and Aihara, S., "The Application of Bulk YBaCuO for a Practical Superconducting Magnetic Bearing," in Proceedings of the Third International Symposium on Magnetic Bearings, 1992.

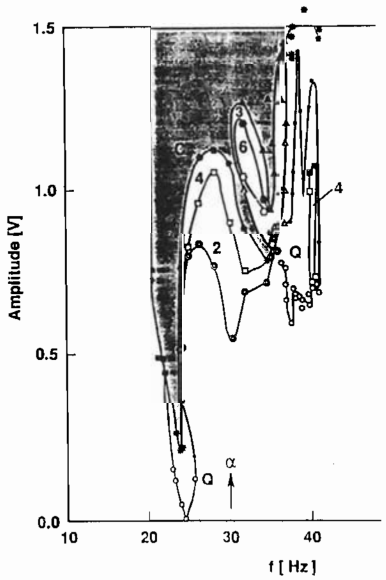

FIGURE 5. Regions of Nonlinear Behavior Force Permanent Magnet Over a Vibrating YBCO Superconducting Bearing