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LEVITATION FORCES AND STIFFNESS OF MODEL ARRANGEMENTS OF MAGNETIC HTSC BEARINGS

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ABSTRACT

This paper describes two configurations of superconducting magnetic bearings for two different applications: a radial bearing designed to support a liquid hydrogen tank but also adpatable for rotating shafts and a planar bearing suitable e.g. for flywheel energy storage systems. These bearings alternatively a linear model of the planar type have been subjected to several tests in setups that have been designed and built especially for this purpose. The experimentally achieved informations about the characteristics and the performance are presented.

Additionally further experiences gained during the measurements are presented concerning possible improvements of the HTSC-array, the excitation system and the design of the bearing housing.

1 INTRODUCTION

Superconducting magnetic bearings (SMB) are very suitable for applications with special requirements like very high relative speeds and vacuum or clean room conditions and thus are an alternative to active magnetic bearings (AMB) or sliding contact and roller bearings. Up to now, the characteristics of SMB's still aren't known well enough to be considered for the design and construction process of industrial applications. Therefore efforts have to be made to investigate the characteristics of SMB's and to define specific design rules. For this purpose at the IMAB theoretical as well as experimental studies have been made.

For further investigations SMB's with different topologies have been implemented (Fig. 1). In two experimental setups they are subjected to several tests to achieve more information about their performance and characteristics.

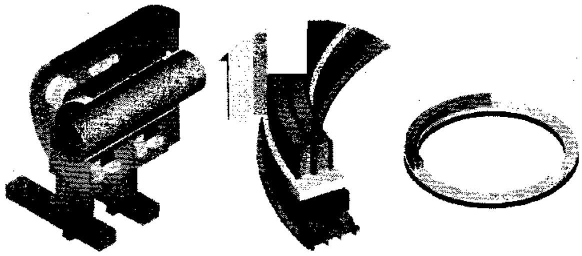

FIGURE 1: Topologies of the investigated SMB's: Radial bearing (left) and planar bearing (right)

2 EXPERIMENTAL SETUPS

The experimental setups are designed to simulate the properties and requirements of the projected applications as realistic as possible.

For this reason the decisive dimensions of the investigated bearings are carried out exactly like the original bearings to avoid mistakes while scaling the results to original dimensions.

2.1 Cooling systems and insulation

The cooling can be provided by electrically powered cryocoolers like Gifford-McMahon, pulse tube or Stirling. Using a Gifford-McMahon cryocooler in our setup the temperature is variable in a range between 45 K and 90 K, controlled by means of a temperature feedback controller. The variation of the temperature gives the opportunity to examine systems characteristics not only at the boiling point of liquid nitrogen at 77 K so that the potentials at lower temperatures can be utilized.

For the presented systems we have chosen a temperature of 65 K, which seems to be a good compromise between the achievable levitation force that increases significantly with lower temperatures and the cooling efforts and in consequence the electric power consumption that increases with a much higher gradient.

A big progress in the design of SMB's is achieved by the thermal separation of the cryogenic environment with the HTSCs and the excitation system with the permanent magnets by means of a super insulation. This insulation allows a temperature gradient of more than 200 K in millimeters of range.

The insulation thickness and therewith the cooling effort competes with the magnetical air gap, which directly effects the achievable forces. To avoid icing of the surface of the dewar, the insulation should have a minimum thickness of two millimeters (including the wall material and the super insulation). Hence, the excitation system is thermally decoupled there is no decay in the remanent flux density B_r of the permanent magnets (PM) that appear at very low temperatures. It would even be possible to have a solenoid actuated excitation system. That means in fact giving up the inherent stability of the PM-HTSC interaction but on the other hand opens up the opportunity to adjust the levitation height during operation.

The thermal separation of the HTSC and the excitation system also makes a SMB easier to adapt to practical applications. The cryosystem – taking into account the special requirements for cryogenic environments – can be implemented similar to the oil pump system of sliding-contact bearings. This makes a SMB suitable for a wider range of applications.

2.2 Force measurement

In the linear system the force measurement is provided by two three axis piezoelectric sensors attached to the excitation system.

The force measurement in the radial bearing is more difficult. Since the excitation system is mounted on the rotating shaft it is not possible to attach force sensors to this part of the machine. Therefore the measuring devices have to be attached to the non-rotating part of the bearing. To avoid deviations due to the stiffness of the bearing housing, the sensors are mounted directly to the copper tube the HTSC rings are fitted in. The functioning of the sensors under cryogenic conditions has been verified. But not only the sensors are located in the dewar, even the charge amplifiers operate in the cryogenic environment very close to the sensors. So a deterioration of the signal quality due to electromagnetic disturbances is avoided.

2.3 HTSC materials

The bulk materials used for the bearings are all monolithic YBaCuO samples. YBaCuO HTSCs provide very high critical currents J_c at the intended operational temperature. In particular the single domain samples with precise oriented c-axis enable large vertical and horizontal forces in interaction with an excitation system with PMs in a flux concentration arrangement.

The trapped field of the used bulk materials averages at 800 mT. With YBaCuO higher trapped fields up to $J_c > 1$ T are possible but this high qualitiy is not reproducable in a batch process.

In the linear modell the four implemented single domain samples have dimensions of 35x35x10 mm^3 (WxLxH). They were produced with the TSMG-process – Top-Seeded-Melt-Growth [1], [2].

At first a radial bearing is equipped with cylindrical single grain HTSCs that were manufactured in a multi-top-seeding melt-texture process [3]. The multi-seeding ensures that the c-axis of the grains has a precise radial orientation to obtain large forces. Even better results were achieved by placing the seeds on the inner surface of the cylinders [4].

Besides the mentioned single domain YBaCuO HTSCs used in the tested bearings there are two further materials taken into account. First there is the polycrystalline YBaCuO with preferred grain orientation produced with the CCG process [5]. Due to the anisotropic orientation of the a-b-planes the obtainable force is not quite as high as the force with the single domain material but the polycrystalline HTSC is more suitable for industrial processing. Even more suitable for an industrial like production is the process of BSCCO HTSCs [6]. Unfortunately BSCCO needs very low temperatures around 20 K for proper operation.

2.4 Planar bearing

The geometry of the linear modell of the planar bearing as implemented in the test bench (Fig. 3) is shown in Fig. 2. The excitation system is positioned by a three axis coordinates table which is controlled by a pc-based control software that also records the measuring results of the force sensors.

The HTSC array is attached to a cold head that is cooled by a Gifford-McMahon cryocooler. In cooperation with a temperature feedback control, the temperature of the HTSC samples can be adjusted between 45 K and 90 K.

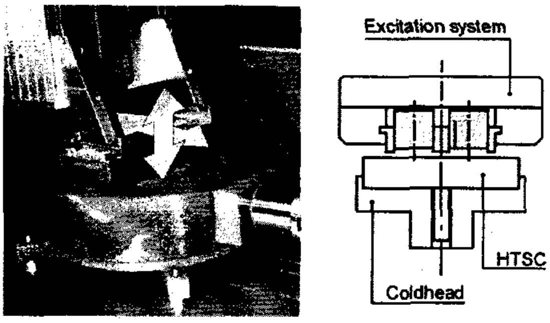

FIGURE 2: Excitation system and dewar with HTSC (left), bearing geometry (right)

FIGURE 3: Test bench for the linear bearing

The field excitation system is a linear flux concentration arrangement with three iron poles. The advantages of the flux concentration arrangement are described in [8]. The field distribution measured in lateral scans at different air gaps from 0.5 to 10 mm is depicted in Fig. 4. A horizontal scan under the excitation system is shown in Fig. 5 and depicts the small variation of the field along the iron poles.

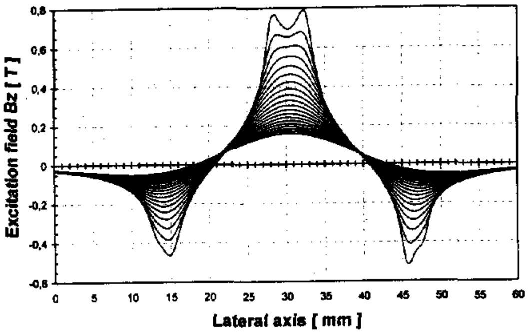

FIGURE 4: Lateral scan of the field excitation system

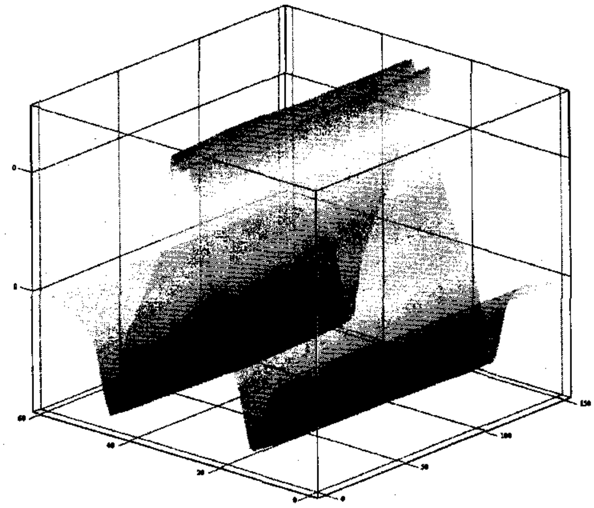

FIGURE 5: Horizontal field scan of the field excitation system

2.5 Radial Bearing

The design of the test bench for the radial bearing was already presented in [8]. Meanwhile the setup has been completed (Fig. 6) and first static force measurements have been accomplished.

For the completion of the bearings a batch of cylindrical HTSCs had to be manufactured (Fig. 7), providing an equal quality to obtain homogeneous forces and stiffness along the bearing. The distribution of the domains and the relative quality was measured using the levitation force (Fig. 8) after a ZFC activation with a PM in a LN_2 environment. The obvious oscillation of the force is a result of the discrete grains with a high J_c and the low J_c at boundary areas. With an infinitesimal small PM zero force would be observed between the grains.

Similar to the prior described linear bearing the excitation system is placed completely outside the dewar for the HTSCs. Therefore the design and the selection of materials of the excitation system doesn't have to meet the particular requirements of cryogenic environments.

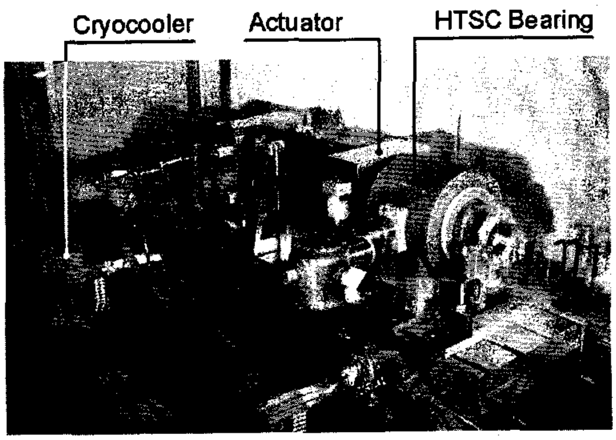

FIGURE 6: Experimental setup for the radial bearing

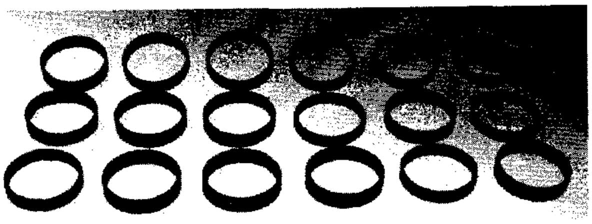

FIGURE 7: Batch of YBaCuO HTSC rings ($\varnothing_a$=100mm, $\varnothing_i$=90mm, h=20mm)

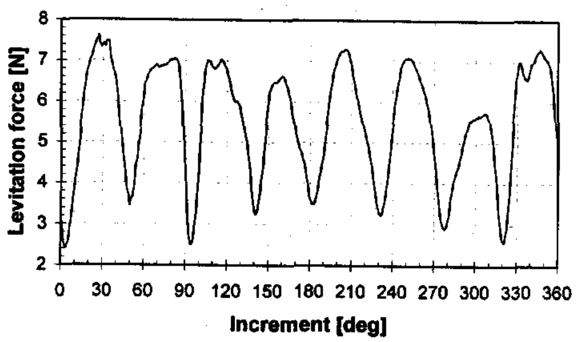

FIGURE 8: Vertical force at 77 K

3 FORCES AND STIFFNESS

3.1 Linear Bearing

The measurements presented below (Fig. 9 and Fig. 10) were performed at a temperature of 65 K after an OFC (Operational Field Cooling) activation and at a magnetic air gap of 3.25 mm.

The results are given as specific values in force and stiffness, i.e. the measured values are given per unit length of the HTSC arrangement. For arrangements using the same standard HTSC bulk materials and with similar clearance the characteristic of the bearing can easily be calculated presuming that the geometric influence of the radius is negligible.

The forces were measured for a displacement of $\Delta z = \pm 0.25$ mm from the cooling position. In the vertical direction the force shows an almost linear dependency on displacement with a slight positive gradient towards smaller air gaps. Hence, the stiffness shows a positive gradient, too. Thus the vertical stiffness is progressive with smaller air gaps.

The horizontal force was measured for a displacement of $\Delta x = \pm 0.25$ mm as well. The force curve is quite symmetric to the point of origin. The small rise of the horizontal stiffness is a result of geometric tolerances in the setup. The stiffness should be constant in the observed region.

The temperature dependence of the levitation force is shown in Fig. 11. The high positive gradient of the levitation force is evident. The gradient decreases with lower temperatures and converges at a maximum specific force of $F_{z,max} = 2.4$ N/mm. This maximum value is given by the limited flux density of the excitation field and the J_c of the HTSC. The chosen operating point at the temperature of 65 K is located on the force curve at the change from the high gradient to the lower gradient so there is not much more force to obtain by applying lower temperatures.

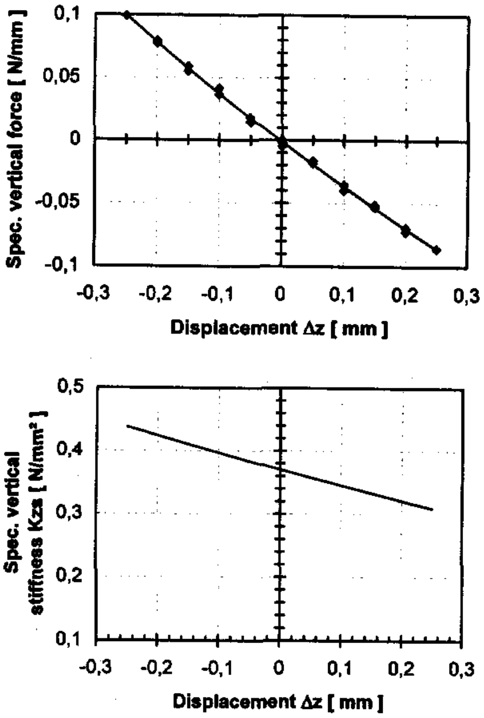

FIGURE 9: Specific vertical force and stiffness at 65 K

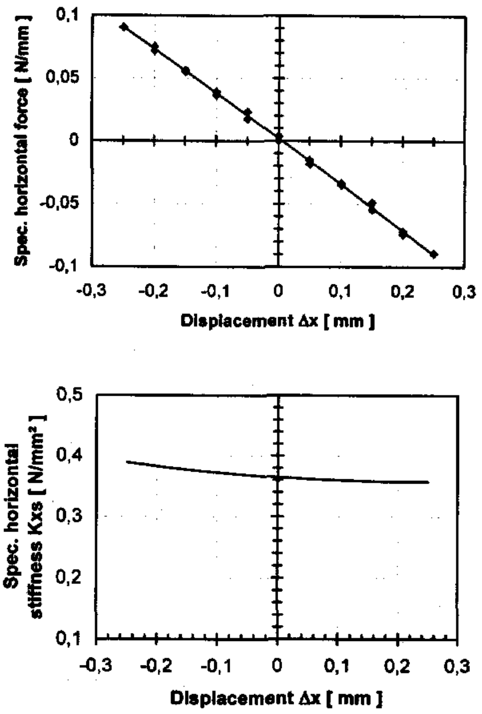

FIGURE 10: Specific horizontal force and stiffness at 65 K

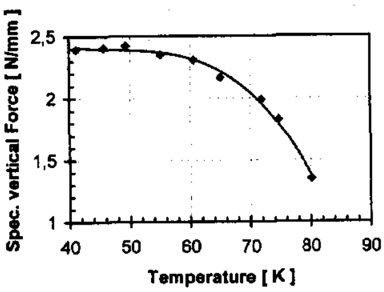

FIGURE 11: Temperature dependence of the vertical force (ZFC)

3.2 Radial Bearing

The gradient of the measured forces and stiffnesses of the radial configuration shown in Tab. 1 are similar to the prior presented measurements at the linear system regarding that the values are always the superposition of the corresponding force curves for increasing and decreasing air gap.

The higher value for the vertical force in comparison to the horizontal force is a result of the different modes of activation. Due to the mass of the rotor the bearing is preloaded in the vertical direction with the consequence of higher force and stiffness at the operating position.

The axial characteristics (y direction) of the bearing are always a factor of two higher than in the x and z direction. This fact is determined by the circular geometry and it becomes obvious when calculating the integrals of the force components.

Table 1: Forces and stiffnesses of the radial bearing

Direction	Force	Stiffness 3)
vertical 1)	545.18 N	366.15 N/mm
horizontal	316.67 N	366.15 N/mm
axial 2)	593.76 N	712.51 N/mm

1) Cooling position at $\Delta z = +1$ mm, measuring position at $\Delta z = -1$ mm

2) Displacement 1 mm of point of operation

3) Measuring position at zero displacement

4 POSSIBLE IMPROVEMENTS

4.1 Material

In bearings that require an array of HTSCs because they exceed the size of a single bulk HTSC, the low J_c between the single bulks has to be considered. Indeed this offers a big potential of optimization, if the HTSCs can be merged together with a conductive contact. First estimations [8] show an increase of the levitation force of about 100% assuming an ideal contact, with properties like the superconducting material itself.

Fig. 12 shows the comparison of the resulting field of an array with three single HTSC's with an ideally merged array under the unaffected field of the excitation system.

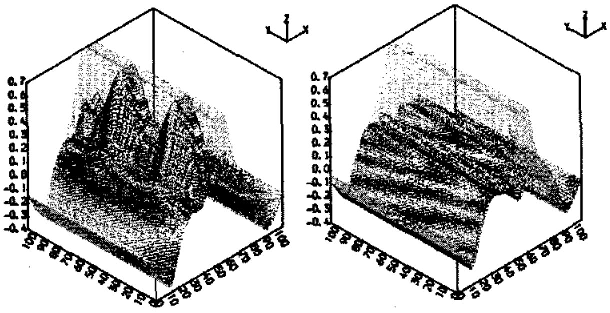

FIGURE 12: Resulting field destribution for single (left) and ideally merged (right) HTSCs

Still the HTSC ceramics don't have very homogeneous mechanical properties in relation to more common construction materials. Subjected to attractive forces the cracks between the a-b-planes can lead to a total destruction of the bulk material. This separation of the a-b-planes can also appear during the cooling process. Due to the anisotropic thermal conductivity that is by a factor 10 smaller along the c-axis than in the a-b-planes the resulting shear stress can damage the probes.

For static and quasi static applications the HTSC samples can be surrounded by a material with a high thermal conductivity like copper or aluminum to obtain a mechanical enforcement and homogeneous temperature distribution. In applications with dynamic variation of the magnetic field on the surface of the HTSC a heating up of the system due to eddy current losses with the consequence of an unadequate increase of the required cooling power has to be taken into account.

4.2 Activation of the Bearing

As the stiffness increases with shorter distances between the excitation system and the HTSC the bearing characteristics can be enhanced by adjustable bearing shells [3] for example.

Another possibility is opened up by the phenomenon that the vertical force increases when the bearing parts are displaced horizontally (Fig. 13).

Further investigations with the linear model have even shown an increase of the stiffness as a result of a horizontal displacement with the vertical gap kept constant as depicted in Fig. 14. After the HTSC was activated with the OFC process the excitation system was moved only in the horizontal direction. The vertical force then was measured for vertical displacement of ±0.5 mm.

Transferred to a radial bearing arrangement the stiffness can be enhanced by applying an axial shift to the rotor. The displacement can be obtained by the weight of vertical rotors for example. In particular, for applications with very small rotor clearance like turbo machines, advantage can be taken of the axial thrust.

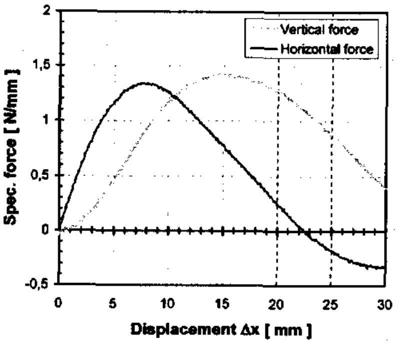

FIGURE 13: Specific vertical and horizontal forces as a result of a horizontal displacement

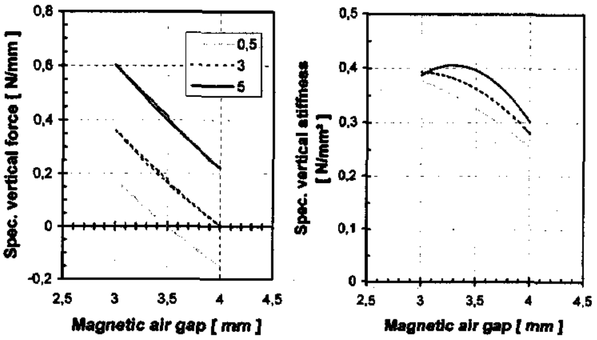

FIGURE 14: Specific vertical force and stiffness after a horizontal displacement

5 CONCLUSIONS

The measurements exhibit comparatively small specific values of load capacity and stiffness. This has to be taken into account for the bearing design for a given rotor. On the other hand a small static stiffness allows low critical speeds and nearly vibration and force free operation of the rotor at nominal speed.

Due to the fact that the load capacity of the axial and the radial direction of planar circular and cylindrical bearings differ by a factor of two the HTSC bearing could probably be utilized more efficiently using electrical machines with disk type rotors. This is caused by the unbalanced electromagnetic pull oriented perpendicularly to the tangential force generating the cranking torque and therewith also perpendicular to the axis of rotation.

For a wider spread of HTSC bearings in industrial applications a system for quality assurance of the HTSC materials has to be established. Further efforts should be directed to the finding of design rules for HTSC bearings suitable for the dimensions of bulk materials processable in batches are needed.

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