APPLICATION OF HTSC-BEARINGS FOR HIGH SPEED MACHINES

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ABSTRACT

This paper describes several configurations for contactless bearings with high temperature superconductors. Different bearing topologies are presented as well as design options for the parts made of superconducting materials and the permanent magnet excitation system. Potentialities for the optimization are discussed.
An example of a cylindrical bearing to support a turbinetype rotor is given with respect to design parameters such as levitation force, stiffness and damping.
The key technology is the method of activating the bearing. At the IMAB a method to affect the levitation force and the stiffness by preloading the bearing and varying the temperature of the superconductor has been developed.

1 INTRODUCTION

Magnetic bearings are used if there is the demand for a contactless and thus frictionless, wearless and oil-free bearing with a minimum of losses. In addition very low efforts for maintenance are needed.
Superconducting magnetic bearings (SMB) are passive bearings that consist of melt-textured high temperature superconductors (HTSC) and a field excitation system of rare earth permanent magnets (PM). Like active magnetic bearings (AMB) they can be used to stabelize rotating shafts or to support and guide machinery parts or vehicles. In contrast to AMB's, the SMB's have an inherent stability: Stable magnetic levitation [4] can be obtained without any electronic feedback control system. This contributes to the fail-safe characteristic of SMB's. In case of a power failure with the aftereffect of loosing the refrigeration, there is a slow change in the temperature due to the heat capacity of the system and therefore no sudden change in the levitation force. The conditional gain of time until the critical temperature T_c is reached can be used to slow down the rotor. Especially for a flywheel energy storage system with its big content of kinetic energy the safety can be increased by the use of SMB's. Immediately after the breakdown, the system can be started-up again with no need for a non scheduled maintenance. Using an active magnetic bearing the rotor drops into the auxiliary bearings with full speed. The bearing will be subjected to heavy wear that shortens the operating life dramatically.
In opposite to active magnetic bearings SMB's are resistant against electromagnetic fields that may cause disturbances in the electronic feedback system with the effect of uncontrolled rotor movements with the worst case of crashing the bearing.
A common advantage of magnetic bearings is the lubrication-free and wearless operation which makes them very suitable for the use under clean room and/or vacuum conditions. It has to be taken into account that despite the absence of friction and wear, additional equipment for cooling and the insulating vacuum is needed. For each application the pros and contras have to be considered.
Using the bearing in a cryogenic environment, such as pumps or tanks for cryogenic liquids, as LH_2 or LN_2, the cooling for the HTSC is obtained without any extra equipment.

2 BEARING TOPOLOGIES

For the Design of a SMB there are three different basic topologies for the arrangement of the HTSC and the PM-excitation system available as depicted in Fig. 1. Depending on its characteristics each of them is predestinated for a particular kind of application.
The axial or thrust bearing (Fig. 1a), specially in a linear version, is suited for levitation and guiding tasks as they appear in transportation systems or, in a circular

arrangemant, for flywheel energy storage systems [1]. The cylindrical (Fig. 1b) and the cone-shaped (Fig. 1c, combination of the radial with the axial topology) bearing can be used for rotating machine parts like shafts and high speed rotors.

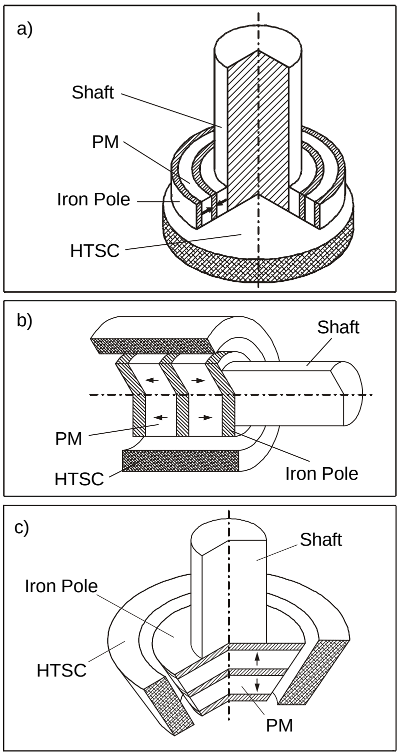


FIGURE 1: Bearing topologies

2.1 The Field Excitation System

To maintain the passive character with the associated inherent stability of SMB's the excitation system is built up using permanent magnets.

There are two different ways to dispose the PM's. Looking at the design with surface mounted PM's, the magnetization is oriented normal to the air gap (Fig. 2a) with alternating direction. The second way is to place the PM's between ferromagnetic poles (Fig. 2b) that concentrates the flux and conducts it to the air gap. Fig. 2 shows the field distribution characteristics.

To obtain the required levitation force for the use in practical applications the bearings usually exceed sizes that can be built up with monolithic PM. Radial magnetized ring shaped PM for the excitation system for a cylindrical bearing with surface mounted PM's are only available with a diameter up to a few centimetres. Composing smaller pieces of PM leads to inhomogeneity of the excitation field. Even large monolithic PM's don't have a perfectly homogeneous magnetization due to manufacturing inaccuracies.

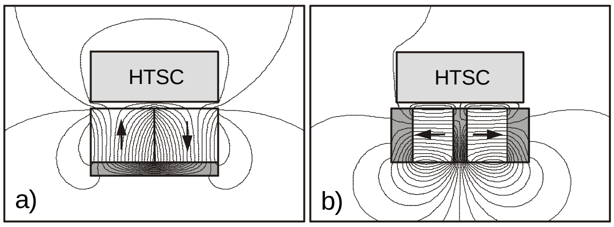


FIGURE 2: Flux distribution in a surface mounted PM's and a flux concentration arrangement

Assuming a translatory motion of the excitation system relative to the HTSC, this part is exposed to a non constant air gap induction. This produces losses due to the hysteresis in the force versus induction curve. As superconductors have a very low thermal conductivity, they may heat up with the effect of local quenching. The critical current density J_c decreases and consequently does the levitation force and the rotor leaves the operating point. The same phenomenon occurs if the bearing is operated with overload. Even when the bearing is cooled down again to operational temperature the rotor will not reach the original levitation height.
Building up the excitation system with flux concentrators, the ferromagnetic iron poles smooth the air gap flux distribution due to their high permeability.

2.1.1 Optimization One way to optimize the arrangement works for surface mounted PM's as well as for the flux concentrator design and varies the ratio of pole pitch and air gap. By means of the pole pitch the bearing can be dimensioned for a maximum of levitation force or a maximum of guidance force. The kind of optimization to choose is determined by the application with respect to design parameters such as orientation of the shaft – horizontal or vertical – and the expected loads.

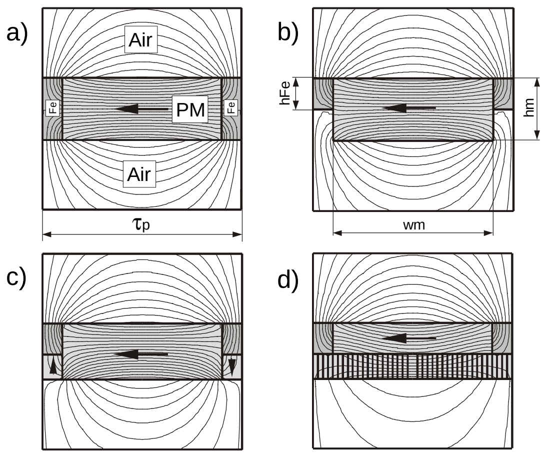


FIGURE 3: Ways to reduce flux leakage on the back side of the excitation system (PM-Mass = const.)

The flux concentration design offers more potentialities to increase the air gap flux density and thus the force generation. The ratio of iron to PM width *wm* can be optimized for a given pole pitch τ_p and air gap δ. Keeping the mass of the PM constant, the air gap induction can be increased by reducing the flux leakage on the back side of the excitation system (Fig. 3a).
Within the same boundary dimensions a better perfomance can be obtained by modifying the PM and iron poles keeping the mass of the PM constant. Exemplary three changes for flux leakage reduction are introduced:

- Shortening of the iron poles *hFe* in relation to the magnet height *hM* at the back side of the system (Fig. 3b)
- Supplementary PM's at the back side of the iron poles (Fig. 3c)
- Screening by means of a multi-polar PM (Fig. 3d)

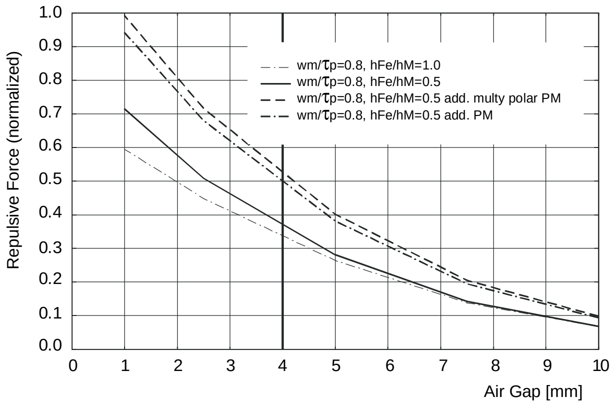


FIGURE 4: Levitation force versus air gap for different flux concentration arrangements (hM = 15mm, PM-mass = const.)

Looking at the modifications to decrease the backward leakage field, the screening with the multi-polar PM offers an increase in levitation force of 50% compared with the primary setup with an air gap of δ=4mm. With additional PM's an increase of 40% can be obtained and with shortened iron poles 10% of the starting value (Fig. 4). The costs for these arrangements will vary in analogy to the gain of the levitaion force.

2.2 HTSC Tube-Sections

The superconductors are melt-textured from YBCO. The ring shaped bulk for the bearing can be assembled out of segments or melt-textured with the muti-seeding method [2] as a complete ring that is shown in Fig. 5.
Regardless the method of producing the ring shaped HTSC, the ring has to be machined precisely to fit in the bearing and to achieve a defined air gap.
Currently the ring shaped bulks assembled from segments offer a higher effective current density accross their boundaries than the multi-seeded rings accross the grain boundaries.

FIGURE 5: Multi-seeding melt-textured ring shaped HTSC [2]

The manufacturing process to choose depends on the progress of the composing method – by varying the welding material – and the multi-seeding process.
The HTSC is built in by brazing it into a copper tube. Therefore it has to be prepared by coating the outer surface to make the brazing possible. After fitting the HTSC into the copper tube, the remaining inner surface of the HTSC has to be sealed to protect it from the air humidity diffusing in which may lead to cracks due to thermal cycling.

3 COOLING MODES

The activation of SMB's is directly linked with the cooling process with respect to the transition to superconductivity and the distance between HTSC and excitation system.
There are three modes of activation to be distinguished (referring to a linear system):

1. MFC – Maximum Field Cooling: The superconductor is cooled down below the transition temperature T_c very close to the excitation system ($\delta_c \rightarrow 0$). The magnetic excitation field is trapped in the HTSC. When the air gap is adjusted to the width of operation δ, attractive forces normal to the surface as well as lateral forces can be achieved.
2. OFC – Operational Field Cooling: The HTSC is located at the operational gap distance ($\delta_c=\delta$) under the influence of the excitation field when the transition happens. Applying a translatory displacement, the bearing responds with guiding forces. If the air gap width decreases or increases the bearing responds with attractive ($\delta_c<\delta$) respectively repulsive forces ($\delta_c>\delta$). To create such a bivalent bearing the cooling method OFCo (Operational Field Cooling with Offset ($\delta_c=\delta+\varepsilon$), Fig. 6) is used.

3. ZFC – Zero Field Cooling: The superconductor is cooled down beyond the range of the excitation field (δ_c>>δ). Decreasing the air gap the HTSC screens the excitation field with the help of the induced currents resulting in stable repulsive forces. Stable lateral forces can not be achieved by this activation method.

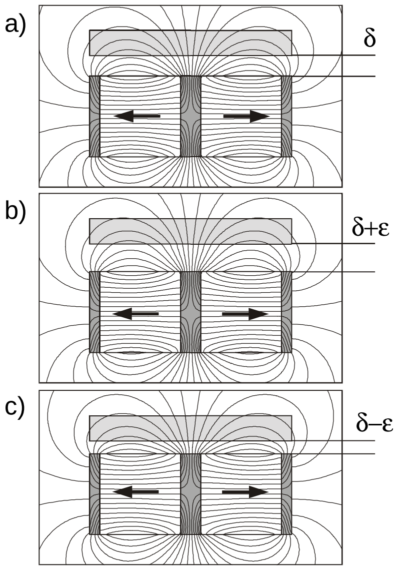


FIGURE 6: Activation method OFC, a) cooling position, b) attractive force, c) repulsive force

Usually the OFC or OFCo process (Fig. 6) is used for the application in SMB's. For MFC and ZFC activation there is mostly not enough space in the bearings air gap.

4 APPLICATION

As an example a turbomachine is equipped with two SMB's. The rotor has two runners with axial thrust compensation and an electrical drive. It is supported by two cylindrical HTSC-PM bearings (Fig. 7a).

4.1 Loads

The bearing has to be capable to compensate the following loads:

– Mass of the rotor (static levitation)
– Radial pertubation from unbalance forces and the unbalanced magnetic pull of the drive
– Axial forces from the axial thrust of the runners (presumed to be almost compensated)

To certify the properties of SMB's of being capable to compensate the mentioned loads, at the IMAB a test bench has been designed able to simulate static, dynamic and transient loads acting on the rotating shaft that can be driven up to 20000rpm by a frequency controlled motor. The rotor in the test bench is supported by two SMB's (Fig. 7b) as described in the following section. The pertubation forces are generated by three electro magnetic actuators (2x radial, 1x axial). The actuators are designed to produce static, dynamic and stochastic forces, i.e. any kind of load cycle can be obtained to simulate an application. The force measurement is done with piezo-electric sensors (Kistler) which are fitted into the bearings as well as in the actuators.

4.2 Design of the Bearing

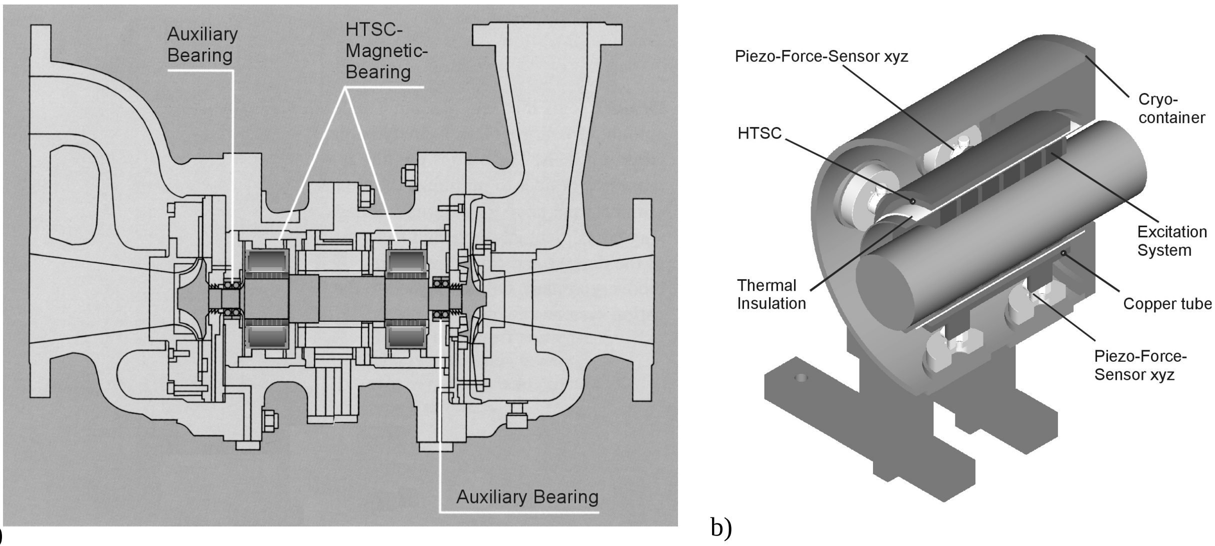
The field excitation system is a cylindrical multi-polar arrangement with six axial magnetized ring shaped PM's and seven iron poles as flux concentrators (Fig. 7b). It is mounted on the shaft and operated under ambient conditions in a warm bore of the dewar for the HTSC. The mechanical air gap width is reduced by a super-insulation consisting of the housing and a multi-layer foil insulation. Surrounding the thermal insulation the HTSC is fitted into a copper tube that insures a constant temperature distribution and also stabilizes the HTSC tube mechanically. Directly attached to the copper tube are four force sensors – two horizontal and two vertical. As a result the connection has a very high stiffness and does not depend on the construction of the bearing housing and the bearing pedestal. 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 deterioation of the signal quality due to electromagnetic disturbances is avoided.
The cooling of the HTSC is provided by a one step Stirling-type refrigerator which is connected to the copper tube via a flexible copper wire. Compared to the refrigeration with liquid nitrogen, the cooling done by a refrigrator is less complicated and more user-friendly in handling. With the refrigerators used in the test bench a cooling output of P_c=15W at T=75K can be achieved with a power consumption of P_{el}=500W.
A cryo vacuum pump filled with active carbon is attached to the cold head of the machine and provides the insulating vacuum during operation, i.e. a supplementary vacuum pump is only needed before starting the refrigerator. Vibrations of the vacuum pump do not affect the measured signals.

4.3 Design Specifications

For the dimensioning of a SMB the following parameters of the application have to be known:

– Static forces – radial and axial
– Stiffness matrix
– Damping matrix
– Frequency dependence of stiffness and damping

The properties of the prototype SMB will be numerically calculated and experimentally investigated and thus validated.



a) b)

FIGURE 7: a) Turbomachine with SMB's, b) prototype of a SMB with integrated force sensors

5 ACTIVATION

The activation of the bearing is done by using two lifting devices that also contain the auxiliary bearings. Before cooling down the HTSC, the rotor is lifted to an empirically determined offset relative to the operating position. The rotor is released when the operating temperature below T_c is reached. Due to its mass the rotor sinks down to operating position.

The activation of the levitation force has to be explained by different modes of activation according to section 3 of this paper depending on the point of the inner tube surface to be looked at. First the intersections with the axis of symmetry are analyzed (Fig. 8a). Looking at point 1, the activation is done by MFC if the available air gap is big enough but usually it is done by OFCo. The same method can be found at point 3. The points 2 and 4 are activated by OFC. The remaining surface elements between the mentioned points are activated by a combination of the two modes.

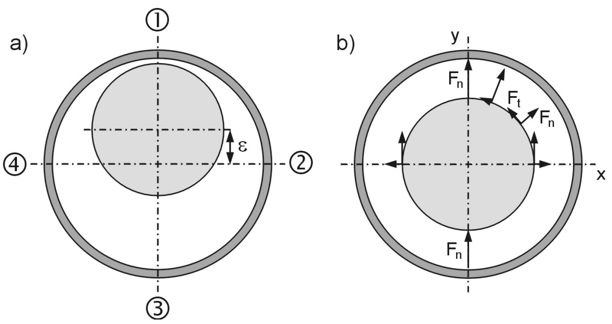


FIGURE 8: Activation of a cylindrical bearing: a) cooling position, b) operating position

Due to the different modes of activation the bearing provides different forces and values of stiffness in the x- and the y-direction. Looking at point 1 attractive forces are obtained, point 3 provides repulsive forces – both normal to the surface – and at points 2 and 4 tagential forces are obtained. The force components pointing in positive and negative x-directions compensate each other due to the symmetry.

The bearing geometry depicted in Fig. 7b ($d_{i,HTSC}$ = 90mm, δ = 4mm, l = 124mm) provides a computed static levitation force of F_y = 483N and a stiffness of k_y = 309N/mm at operation position.

Because of the very low damping characteristics of SMB's an external additional damper becomes necessary, e.g. a friction damper or a damper by means of oil.

The obtainable preloading of the bearing is limited by the width of the air gap and the rotor mass. If higher values of levitation force and stiffness are required, a new solution of activating and preloading the bearing has to be introduced. At the IMAB a method of activation is developed allowing the adjustment of the air gap as needed in order to achieve the required preloading without changing the rotor position (Fig. 9).

This bearing design enables applications that do not allow a displacement of the rotor position, i.e. turbomachinery, because of very small runner clearance. So the activation is not done by lifting the rotor but by spreading the HTSC shells to a δ_c required for the preloading, cooling down below T_c and then adjusting the air gap to the operational value. This bearing design gives the opportunity to adjust different air gaps for the upper and the lower shell. Maximum values of attractive force (position 1 in Fig. 8) and repulsive force (position 3 in Fig. 8) can be obtained by using the same excitation system despite these two positions having their optimum at different air gaps.

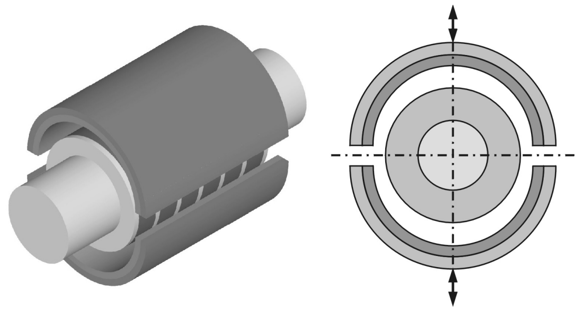


FIGURE 9: Activation by the displacement of splitted HTSC shells

6 SHAFT POSITIONING

In this context the phenomenon of flux creep [3] has to be mentioned. If a SMB is loaded with a static force the levitation force shows a time decay but then remains on a constant level. This loss of levitation force with the effect of a drift in the levitation height can be compensated by the movable HTSC shells. The rotor is not displaced from the operating position.

In the same way manufacturing tolerances concerning the HTSC shells [5] as well as the excitation system can be compensated because one empirically determined cooling offset usually is not suitable for two identical bearings if an exact operational position is demanded.

Levitation force and stiffness are not only determined by the geometry of the bearing but can be influenced by the temperature as well (Fig. 10).

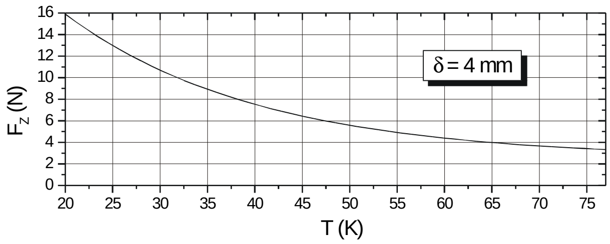


FIGURE 10: Typical temperature dependence of the levitation force

If the setup provides a change of temperature the operating position of the rotor can be adjusted by reactivating the bearing with a modified temperature.

It is also possible to reduce flux creep by lowering the temperature after activating the bearing and adjusting the rotor in the operating postion. For a temperature feedback control it can be assumed that the cooling is provided by a refrigerator instead of the use of LN_2. For big changes the temperature control is achieved by changing the rotational speed of the cryo-coolers drive. The precise adjustment is done by a heating coil placed directly on the cold head of the refrigerator.

The test bench momentarily designed and constructed at the IMAB is capable to simulate all of the above mentioned aspects. The measurement results will show the temperature effect on force and stiffness for the cylindrical bearing topology.

7 CONCLUSIONS

The so far done investigations for the support of rotors by SMB's show that the use of HTSC's is a very complex but especially for certain applications very promising technique. A way to activate the bearing with the rotor remaining in operating position has been presented. This is presumed to be one of the key techniques for the application of SMB's.

The developement of bulk HTSC's with different shapes is still carrying on and a steady increase of the obtained levitation force and stiffness can be expected.

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