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L. Jazdowski / R. Palka

3D-Modelling of Interaction between Multigrain HTSC and Magnetic Field Systems

INTRODUCTION

The recent development of melt-textured high temperature superconductors (HTSC) enables new designs of passive superconducting magnetic bearing (SMB), where the magnetic forces between the permanent magnets and the superconducting bulks can be used to support and stabilise a rotor shaft or a vehicle. Superconducting magnetic bearings are based on inherently stable force interaction between the field excitation system and HTSC bulks. Of outstanding interest is their use for high speed machines e.g. turbo machinery, or rotating energy storage systems and for linear and two dimensional planar transport systems ([1],[2]). The conceptual simplicity of HTSC magnetic bearings contrasts with the complex magnetic behaviour of the implied materials. The economical usage of any devices with HTSC bulks depends on the intensity of interaction between the external magnetic field and HTSC. The optimization of any superconductor system causes the necessity of development of very precise calculation methods. These must be adequate enough to be applied while designing different practical configurations. The demagnetising effects associated with the finite dimensions of the superconducting samples, the inhomogeneity of the applied field, the hysteretic magnetisation of the superconductor and its anisotropic current conduction are some of the aspects to be considered when modelling the HTSC-external field force interaction ([1],[2],[5],[6],[8]).

MODELLING OF 2-D INTERACTION

Figure 1 shows the main parts of linear superconducting magnetic bearing consisting of the field excitation arrangement and HTSC-bulks.

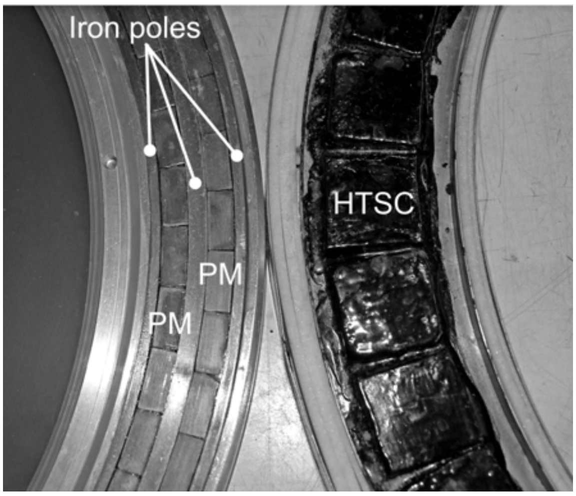

Fig. 1 Linear superconducting bearing: Field excitation system
(flux collecting arrangement) and HTSC-bulks

The magnetic behaviour of type-I superconductors is characterised by the Meissner effect, where reversible surface currents are induced in the superconductor to perfectly screen the applied magnetic field. The Meissner state in the HTSC can be observed as long as the external field is lower than the first critical magnetic field H_{C1}. However, this perfect diamagnetic model may be used for determination of a theoretical force limit by design and optimisation of repulsive HTSC-PM configurations. Type-II superconductors (known as the hard superconductors) allow some penetration by the external magnetic field into their region. This field can be trapped by a superconductor, when cooling below T_C. For modeling of superconductivity the classical vector potential definition has been used. In the 2D quasi-static case the magnetic vector potential $\mathbf{A}$ can be obtained from the Poisson equation (linear case):

$$\nabla^2 \mathbf{A} = -\mu_0 \mathbf{J} - \mathrm{rot}\mathbf{M} \,, \qquad (1)$$

where $\mathbf{J}$ denotes the current density vector and $\mathbf{M}$ the magnetization vector.

For each HTSC-PM structure there are different activation modes possible:

1. ZFC (zero field cooling): $g_{act} >> g_{op}$,
2. OFC (operational field cooling): $g_{act} = g_{op}$,
3. OFCo (operational field cooling with offset): $g_{act} \approx g_{op}$,
4. MFC (maximum field cooling): $g_{act} \approx 0$ mm.

For the OFC activation the SMB operates in the same position in which it is cooled. This occurs under zero gravity conditions in the free space, or if the weight is compensated by other device. For MFC and ZFC activation there is mostly not enough space in the bearings air gap. The typical activation mode for SMB is OFCo, where the operational position of HTSC differs minimally from the activation position. For small displacements of the excitation system, the perfectly trapped field model of superconductivity should be applied ([1],[3],[5],[6]). This algorithm requires that the field distribution in the initial position of HTSC and two field distributions of the Meissner state in the initial and final position of HTSC have to be determined. The final field distribution can be obtained as an appropriate combination of the vector potentials from these three initial calculation steps [5].

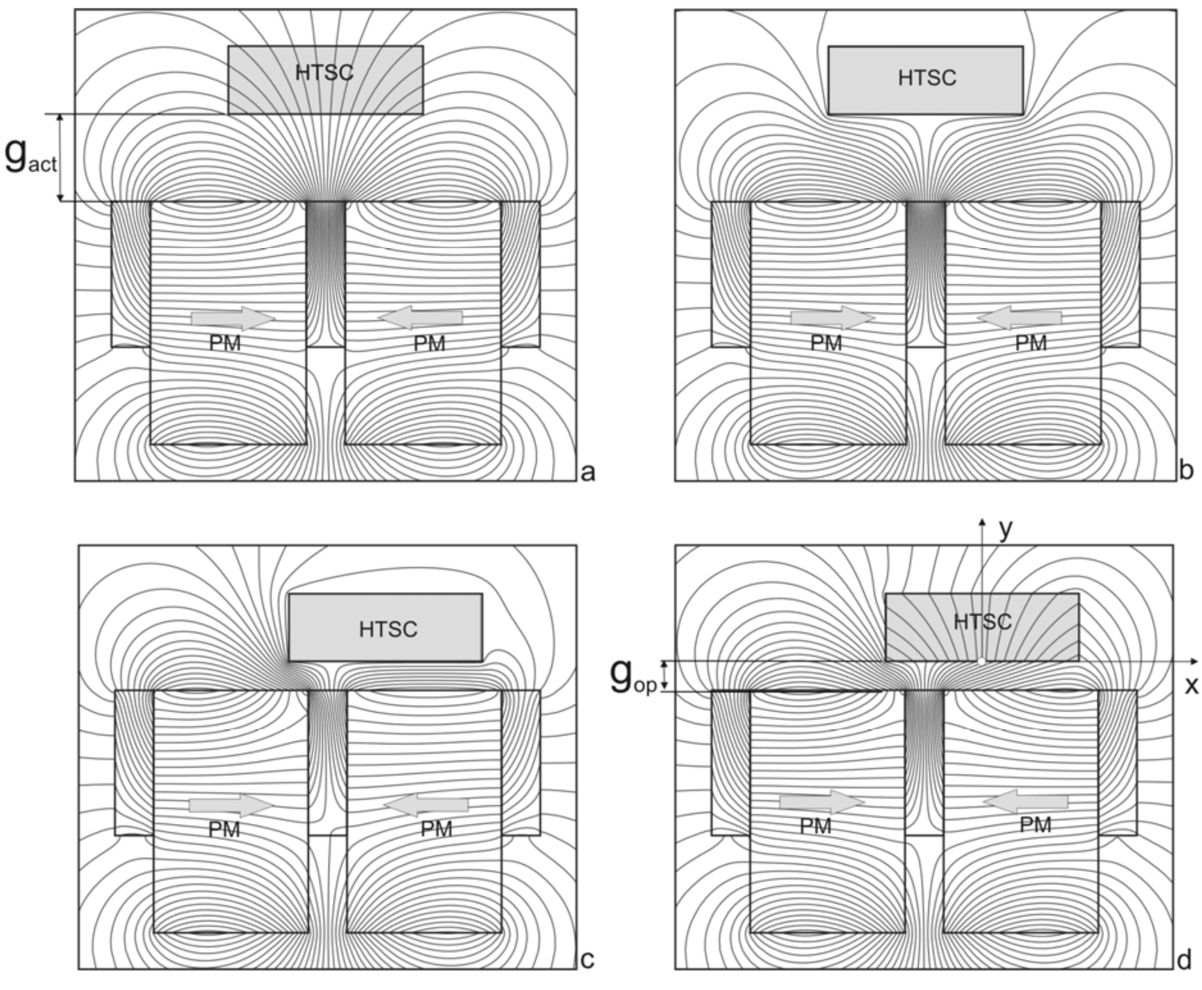

Fig. 2 Four steps for the calculation of the magnetic field distribution within the HTSC-bulk moving from one position to another:

a: HTSC in the activation position g_{act},

b: HTSC in the activation position g_{act} in the Meissner state,

c: HTSC in the operating position g_{op} in the Meissner state,

d: HTSC in the operating position g_{op}

The perfectly trapped magnetic field within the HTSC from the initial (activation) position $g=g_{act}$ (Fig. 2a) in the final (displaced, operational) position $g=g_{op}$ calculated by the proposed method has been depicted in Fig. 2d. As can be seen, the magnetic field within the HTSC remains unaltered; it means that forces acting in both directions can be observed.

3-D APPROACH

Under assumption that the excitation system can be treated as perfect homogeneous in the direction of motion, all force calculations could be carried out in a two-dimensional plane orthogonal to the direction of movement. In reality neither the magnets of the excitation system nor the cluster of superconductor bulks are perfectly arranged as one uninterrupted unit. For further improvements of the force predictions the 2-D trapped flux calculation model has been extended for 3-D cases. Figure 3 shows the principal 3-D excitation system for linear superconducting bearings. The task depends on the calculation of the magnetic field in this configuration by any movement of the HTSC-bulk.

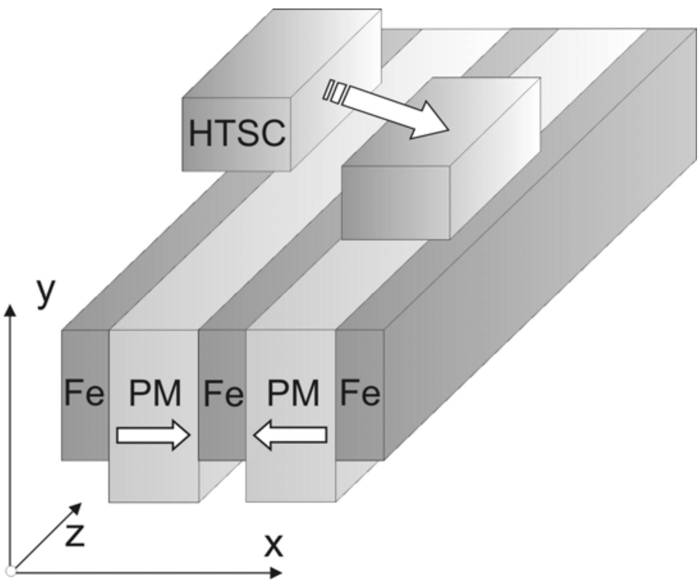

Fig. 3 3-D field excitation system for superconducting bearings
in a flux collecting arrangement

To compute this interaction an advanced 3D-algorithm has been applied. This algorithm is based on 3-D scalar potential formulation using the perfectly trapped field model ([3],[6]). Introducing the scalar potential $\mathbf{H} = -\mathrm{grad}\,V$, the following well known equation describing the 3-D magnetic field is obtained:

$$\mathrm{div}(\mu \,\mathrm{grad}\, V) = \mathrm{div}(\mu \mathbf{H_J}) \,, \qquad (2)$$

The 2-D algorithm described in the previous section can be extended to the 3-D field calculation and Eq. (2) can be used for the appropriate 3-D FEM formulation. By this approach the scalar potential distribution within the HTSC-bulk from the initial position has to be moved to the new position (four calculation steps). The resulting system of FEM algebraic equations (usually up to 600000-800000 unknowns) has to be solved iteratively with the highest accuracy. This 3-D calculation algorithm, developed at the Institute of Electrical Machines, TU Braunschweig, Germany, is able to consider imperfect excitation systems with not matching permanent magnets and also interrupted iron structures [6]. Furthermore, HTSC clusters composed of individual, electrically insulated HTSC bulks can be considered for more sophisticated force determinations. Exemplary results of the field calculation for single domain HTSC-bulk have been shown in Fig. 4: Fig 4a illustrates the magnetic field distribution within the HTSC on the surface cutting the superconductor in the middle and Fig. 4b shows the current density distribution on the upper surface of the superconducting bulk. The values of the surface current have been determined from the field continuity condition at the interface between two media.

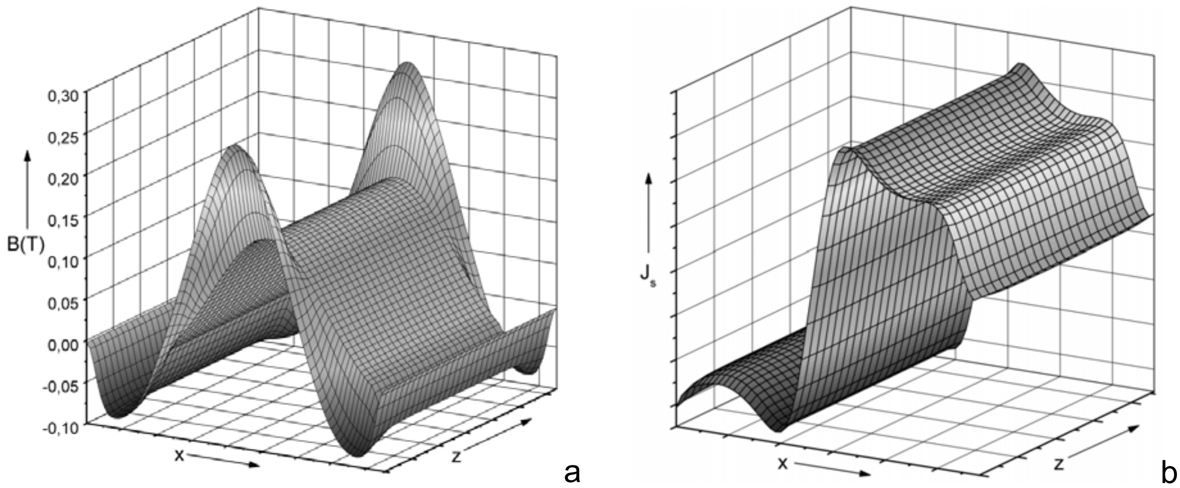

Fig. 4 a: Magnetic field distribution within the HTSC in the operating position (y-component)
b: Current density distribution on the upper surface of the HTSC-bulk in z-direction

The same method can be applied for the HTSC-bulk consisting of many separated and irregular grains (as shown in Fig. 5a), for regular multigrain HTSC-bulks, or for arrays of HTSC-bulks. For these calculations the knowledge of the size and position of superconducting regions is necessary [7]. Some results of the 3-D field calculation for the regular multigrain superconducting bulk consisting of 4, 9 and 16 sub-bulks have been shown in Fig. 5b ([3]).

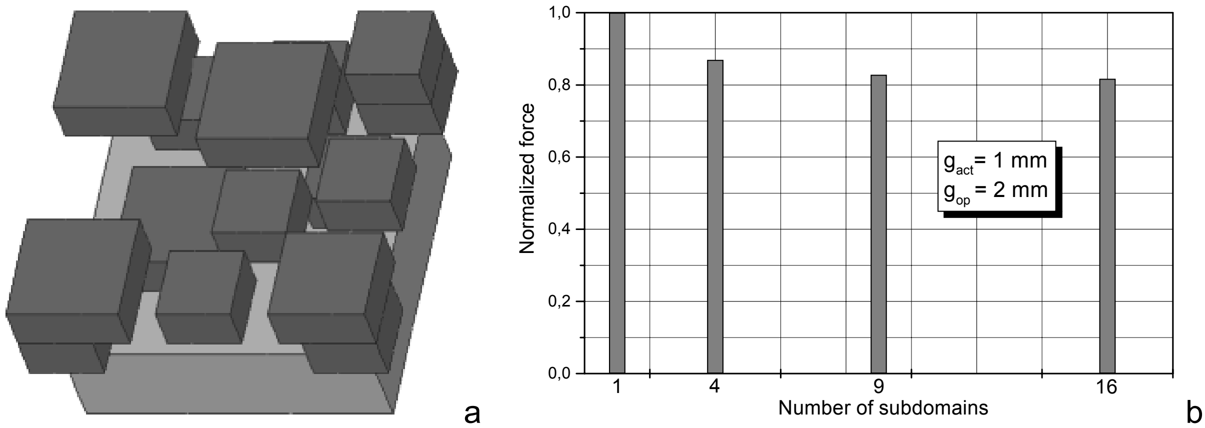

Fig. 5 a: Multigrain HTSC-bulk acting with the PM
b: Normalized force for multigrain HTSC after OFCo activation

Based on two or three dimensional field calculations, the optimal designs for the excitation systems for superconducting bearings have been determined. They depend on the activation mode and cooling gap strongly and constitute always compromises between the requirements on the forces and the stiffness in all directions. All such quantities of the SMB can be numerically calculated and optimized by using of the appropriate numerical algorithm described above.

MEASUREMENTS

Validation of the calculated forces has been done by measurements in the set-up shown in Fig. 6.

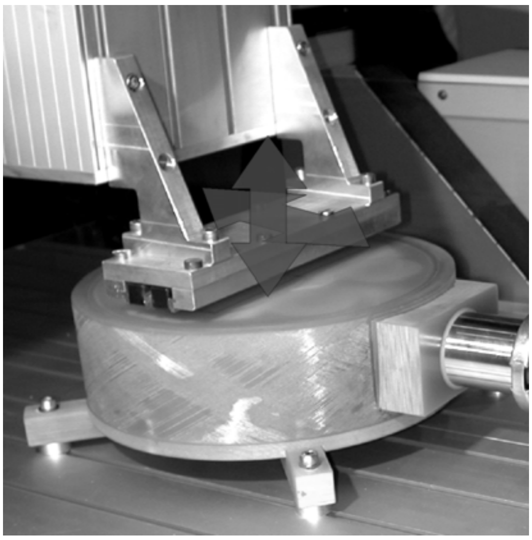

Fig. 6 Force measurement set up (3D-co-ordinate table)

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 and a vacuum pump is attached to the cold head of the machine and provides the insulating vacuum during operation. The field excitation system can be moved in each direction and the resulting forces can be measured.

SMB FOR THE FLYWHEEL DYNASTORE

Configuration from Fig. 3 can be used for contact-less linear transport. This arrangement has also been applied for the suspension of the DYNASTORE flywheel [6]. This flywheel is designed as a high speed energy storage system for events of a short duration, to serve for the local tuning of the medium voltage power grid. As the energy converter a switched reluctance machine has been applied, because it does not require any rotor excitation and offers lossless operation at the stand-by phase of the energy storage. Such machines are also characterised by a very simple, robust rotor construction and very short excitation times thus featuring a fast response of the storage within one- to two milliseconds. The flywheel configuration uses a high speed switched reluctance machine with external rotor, with a rated power of 2MW at the speed range between 6000÷10000 rpm. The machine rotor is fully integrated in the flywheel construction utilizing the full volume and power density potential of the storage. The advanced high temperature superconducting magnetic bearing system used minimises the stand-by losses while maximizing bearing stiffness. The concept of this flywheel energy storage system is depicted in Fig. 7.

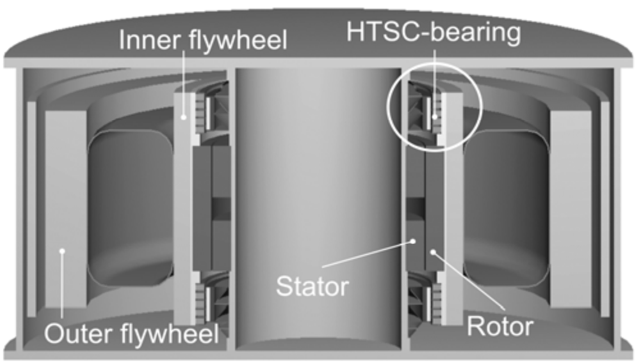

Fig. 7 Flywheel as the energy storage with radial SMBs (Dynastore-Project)

The details of the superconducting bearing used by the above energy storage system have been shown in Fig. 8a. The flywheel from Fig. 7 can also be supported by the axial bearing illustrated in Fig. 8b.

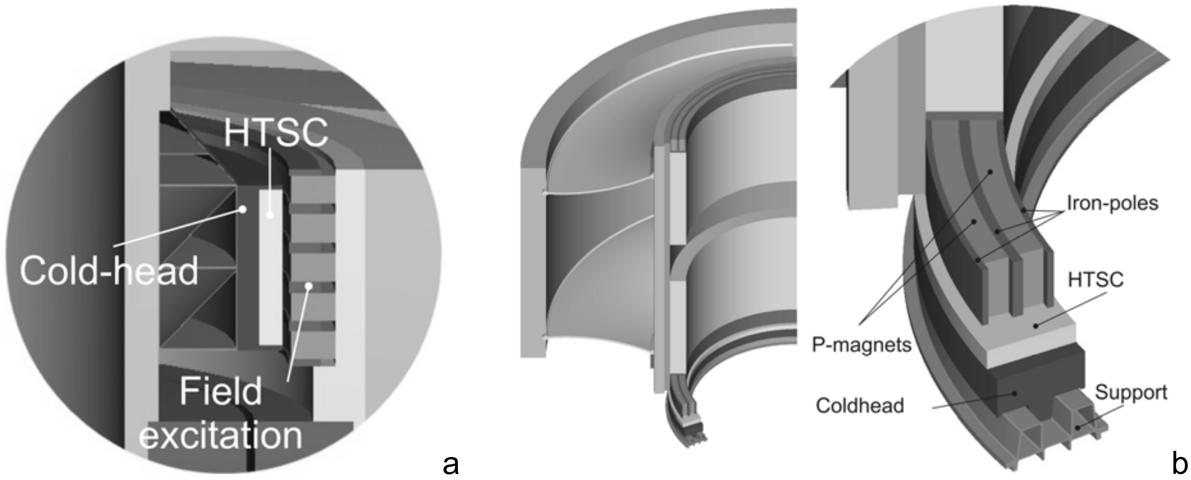

Fig. 8a: Radial superconducting bearing for the flywheel from Fig. 7
b: Axial superconducting bearing for the Dynastore-Project

SUMMARY

The paper deals with two numerical algorithms for the evaluation of the HTSC reaction on the external magnetic field. The 3-D numerical approach enables the calculation of the magnetic field distribution in any field configuration by the movement of the HTSC-bulk and for any imperfectness of the field excitation system and the multigrain HTSC bulk. An example of the superconducting bearing used for a flywheel optimized by the above methods has also been shown.

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