Mean Field J_C Estimation for Levitation Device Simulations in the Bean Model Using Permanent Magnets and YBCO Superconducting Blocks

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This work presents a mean field estimation of J_C as a bulk characteristic of YBCO blocks. That average J_C allows a good fitting of the finite-element-method (FEM) simulation of the levitation forces to experimental results. That agreement is quite enough for levitation requirements of device projects, at short gaps and zero field cooling process, within the Bean model. The physical characterization for that estimation was made measuring the interaction force between the PM and one YBCO block in 1-D and mapping the trapped magnetic field in those blocks in 2-D.

I Introduction

Superconducting melt textured (MT) YBCO blocks are extremely important materials to the development of stable levitating devices as bearings, for example. The design of levitating systems (as linear or rotating bearings) using high temperature superconducting (HTS) materials requires large bulk specimens with highly aligned and well connected grains [1]. This is achieved using melt textured growth (MTG) process, usually by top-seeding methods [2]. Such samples allow large current loops and high values of J_C.

The use of finite element method (FEM) improves the project of levitating devices. But in order to apply a commercial FEM software, the response of the MTG HTS block to an applied magnetic field must be informed by the user. That response is represented by a B = B(H) curve [4] for each particular sample considered. To our knowledge, up to date, there is not any FEM software able to work with HTS materials properly. However, within the framework of the Bean Critical State Model (BCSM) [3], the B = B(H) can be constructed, once the mean field value of J_C is known. Thus, the projects of any levitating devices using FEM requires the use of the value of J_C [5].

That *actual* J_C value is a parameter that depends on the overall structural features of the MTG *Type-II* HTS blocks (mainly on the distribution of pinning centers). The *mean* J_C has usually been evaluated using only a *small* piece extracted from the MTG block. With its magnetic moment measured with a vibrating sample magnetometer (VSM), one can evaluate the J_C by the BCSM [3]. That evaluation has the inconvenience of damage or destruction of the block to be used as levitation element and, additionally, that result is strongly dependent on the particular local of the sample extraction. A *desirable* evaluation of J_C must use a non-destructive and overall (*bulk*) response of the specimen, instead of a localized one.

We propose a non-destructive methodology to evaluate the average ("Bean") J_C value used in FEM simulations, which is accurate enough to project levitating devices. The overall, or bulk, response used to validate the J_C value comes from the "levitation force" curve of the specimen.

II Methodology

The proposed methodology employs finite element method (FEM) and the BCSM in order to simulate the interaction force between a permanent magnet (PM) and a MTG HTS block, the so called "levitation force" [5]. The flux density B due to the magnetization response M to the applied field H is expressed by usual relationship $B = \mu_0(H + M)$, where M is also a function of the geometry. By using the BCSM, for cylindrical symmetry with radius R, one has the following relation:

$$B(H) = \mu_0 \left[\frac{H^2}{H_P} - \frac{H^3}{3H_p^2} \right] \qquad (1)$$

where $H_P = J_C R$ is the full penetration field [3]. As the sample radius R is measured, J_C is the only free parameter. The value of J_C can be adjusted to generate the B(H) curve of the MTG HTS levitating block that allows the FEM software to reproduce (simulate) the *measured* HTS-PM interaction force ("levitation force") curve.

We used as MEF software the *ANSYS Multiphysics 5.7* [4] and the PM-HTS interaction (levitation) force was calculated using Maxwell Tensor approach [4].

The levitation force measurements employed a software controlled equipment (built in *LASUP* in cooperation to *ICMAB* staff personnel) where a SmCo PM (diameter ϕ = 19.00 mm, thickness t = 6.40 mm, surface central field B_S = -0.169 T) is attached to a commercial load cell (UTILCELL, mod 120). Quasi static measurements are performed (0.2 mm each step, 2.5 mm/min scan) while the SmCo PM vertically *approaches* to a tightly fixed MTG HTS block at 77.4 K (*ZFC*). A set of eight cylindrical MTG HTS YBCO composites (123+211) blocks made by the same method [6] was analyzed. Once all of them were made with the same conditions and have the same geometrical features (diameter ϕ = 26.00 mm and height h = 17.00 mm), the J_C value, $B(H)$ curve and reaction force in response to the approaching SmCo PM should be essentially the same for all of them.

The SmCo B(H) curve is already present in the *ANSYS* data bank and the MTG HTS B(H) curve was built changing the J_C value until the best fitting of the levitation force curves was found.

The MTG HTS blocks were also characterized by 2D mapping of the trapped magnetic field. A BRUKER electromagnet was employed as homogeneous field source, the applied field was 0.5 T and the mapping was made using a Hall sensor (TOSHIBA, mod THS118) attached to a software controlled X-Y positioning table built at LASUP (0.4 mm each step, 1mm/s scan, total area scan time ~ 30 min).

III Results and discussion

The best mean field J_C value found was 7×10^7 A/m^2, of the same order of magnitude of the measured values in those kind of samples by VSM and BCSM. The best B(H) curve is shown in Fig 1. The simulation by FEM was best performed with that curve, see Fig 2, and all the measured levitation force curves were well fitted, as can be seen in Fig 3.

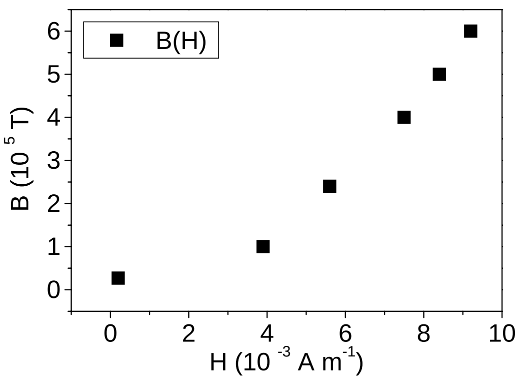


Figure 1. The best B(H) input data for the MTG HTS blocks with same dimensions (see text).

The field mapping of the blocks is presented in Fig 4. As can be seen, the maximum trapped field is almost the same to all samples (2.5 kG = 0.25 T), but the *profile* changes from sample to sample, mainly for larger distances from the center.

That average J_C value allowed a simulation of the levitation force in all the measured range (40 mm) not sensitive, in linear scale, to those different trapped field profiles.

Details of the levitation curves, seen in Fig. 5 at logarithmic scale, show that for small distances (less than 5 mm) the simulated and measured curves are in good agreement for all samples. For large distances (separation greater than 20 mm) some simulated force curves deviate from the measured ones without any clear pattern. However, the distances smaller than 5 mm are the usual ones employed in levitation devices.

Once the field mapping indicates each block has different current loop profiles, the use of Bean model was not able to take into account such non homogenous feature in order to generate the B(H) response curve. But the results indicate such deviation do not affect simulations devoted to levitation projects.

New studies are now on their ways in order to evaluate the relation among the levitation force curves, the best average J_C value and the topological deviations in real field trapping from the predicted by BCSM.

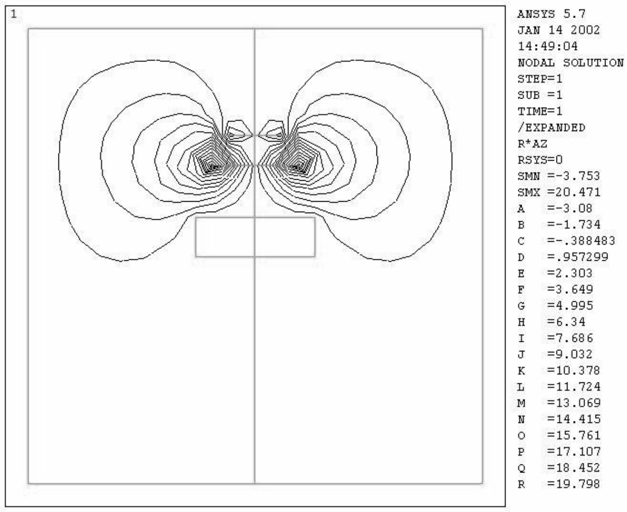


Figure 2. Simulated interaction between the SmCo PM and the MTG HTS block. Separation distance between them varied within two ranges: 0.5 mm and 1 mm steps.

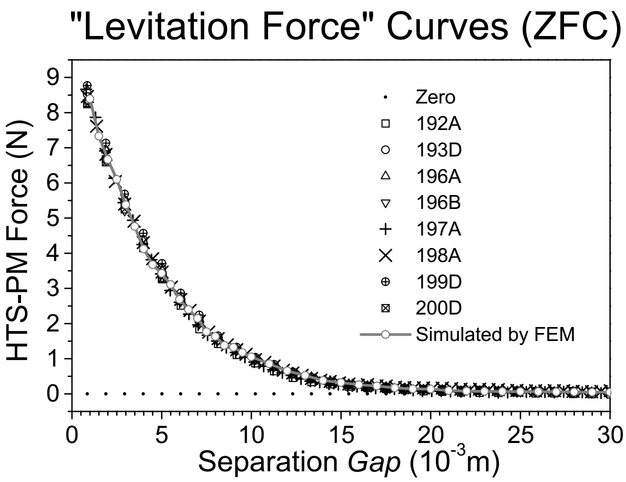


Figure 3. Measured and simulated PM-HTS interaction ("levitation") force curves as function of PM-HTS separation gap, linear scales.

IV Conclusions

We proposed and employed a non-destructive new methodology to estimate the mean field J_C of large MTG HTS blocks, based on an overall ("bulk") response: the levitation force curve.

In our approach, that average J_C value is a free parameter used to construct the B(H) curve of the MTG HTS block, as required by the FEM software to simulate its levitation force curve. The evaluated J_C is validated to levitation requirements of device projects by the good agreement between *directly measured* and *simulated* levitation force curves, specially at small distances.

For larger gaps between the PM and the MTG HTS block, our results are sensitive to the trapped magnetic

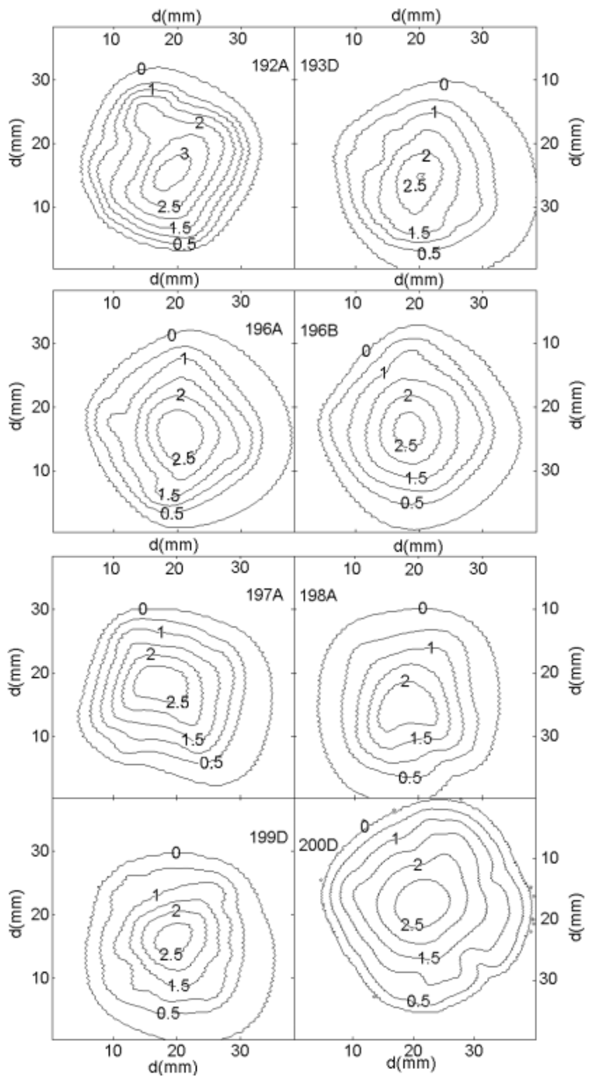
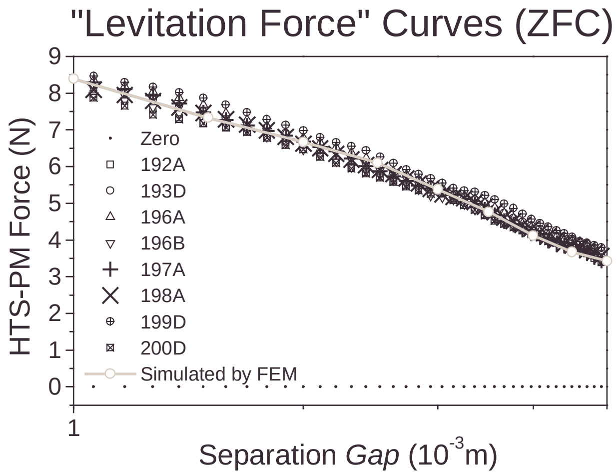
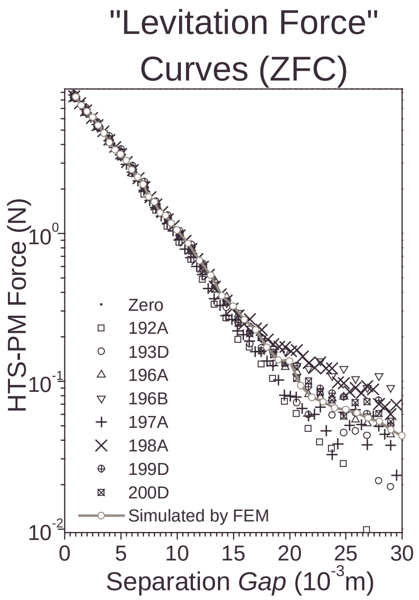


Figure 4. The 2D trapped magnetic field mapping of all samples, B values in KG.



(a)



(b)

Figure 5. Details on measured and simulated PM-HTS interaction ("levitation") force curves, logarithmic scales (see text): (a) small gaps and (b) large gaps.

field *profile* of the sample, not only to the maximum trapped field value, but in a non conclusive way yet.

Once our methodology does not require a sample with small dimensions and uses the overall behavior of the MTG block, we also proposed it as an alternative to the local response and destructive ones usually employed.

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References

[1] F.C. Moon, *Superconducting Levitation: applications to bearings and magnetic transportation*, John Wiley & Sons, Inc., New York, USA, 1994.

[2] G. Desgardin, I. Monot, B. Raveau. "*Texturing of high-T_C superconductors*", Supercond. Sci. Technol. **12**, R115 (1999).

[3] C.P. Bean. "*Magnetization of Hard Superconductors*", *Phys.Rev Lett.* **8**, 250 (1962); "*Magnetization of High-Field Superconductors*", Rev. Mod. Phys. **36**, 31 (1964).

[4] ANSYS 5.7 User's Manual, Ansys, Inc., 2000.

[5] A.S. Pereira, G.C. da Costa, L. Landau, and R. Nicolsky, *"Finite element simulation of selfstable permanent magnet-superconducting rails"*. *Proceedings of the EUCAS'99 – European conference on Applied Superconductivity*, IOPP, Bristol UK, 2000, p 108; G. C. Costa, L. Landau, R. Nicolsky. "Cálculo de Forças de Levitação em Trilhos Supercondutores via Método de Elementos Finitos", *Proceedings of the 20^{th} Iberian Latin American Congress on Computational Methods in Engineering*, P. M. Pimenta, R.M.L.F. Brasil, E.S.A. Neto, Eds. (CD-ROM edition, 1999).

[6] K. Salama, *personal communication*.