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 desimble 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:

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

(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 levitation 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 \( \phi = 19.00 \) 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 (ZF). 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 \( \phi = 26.00 \) 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 homogenous 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 \( \sim 30 \) min).

### III Results and discussion

The best mean field \( J_C \) value found was \( 7 \times 10^7 \) 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).](image)

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 \((2.5 \text{ kG} = 0.25 \text{ T})\), 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 \((40 \text{ mm})\) 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 \((\text{less than 5 mm})\) the simulated and measured curves are in good agreement for all samples. For large distances \((\text{separation greater than 20 mm})\) 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.

"Levitation Force" Curves (ZFC)

![Graph showing levitation force as a function of separation gap](image)

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.
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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