Comparison of properties of a bulk HTS and a stack of HTS tapes after FC and ZFC

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Abstract. This paper presents the results of the analysis of properties of a high-temperature superconducting (HTS) material in two forms - HTS bulks and a stack made of a number of HTS tape layers. Stack of HTS tape is a new type of application of superconductors, which can be used instead of a convention bulk material. In this work, we study the levitation properties of HTS stack and compare it with the same characteristics of HTS bulks to find the effective way of modelling such type of HTS. Experimental measurements of the force interaction between a permanent magnet and HTS material, as well as a "trapped" magnetic field, are performed for both types of a superconductor. The HTS samples are analysed in the case of Field Cooling (FC) and Zero Field Cooling (ZFC). The aim of the research is to analyse experimental results to compose and justify mathematical models for calculation magnetic system with such types of superconductor.

1. Introduction

A number of publications of various research groups around the world are devoted to the study of the possibility of using 2G HTS tapes to create stable magnetic levitation. The main directions in this area include the applying of HTS tapes as elements with a “trapped” magnetic field and the use of HTS coils or windings.

In the case of using HTS tapes in form of superconducting windings, two ways are possible: creating short-circuited structures, or connecting a superconducting winding to a voltage source. Studies of the force characteristics between the permanent magnet and the HTS winding in [1] have showed the ability to provide levitation in both versions. However, noticeable decrease of the force over time is observed using short-circuited windings, which is associated with losses that occur at the point of tape connect, since the contact resistance exceeds the resistance of the superconducting layer of the tape. In the case of magnetic levitation, a solution to this difficult could be the magnetic suspension proposed in [2,3] using non-contact superconducting loops. But the manufacture of such loops is a rather time-consuming process, and the form and technology of their manufacture impose some restrictions on their use in magnetic supports.

Another direction of using HTS tapes is superconducting current windings, which in fact is an alternative to classical copper windings. The greatest interest in such windings is observed in the field of electrical machines, but they can also be used to create magnetic levitation, for example magnetic
bearing for flywheel energy storage system [4]. Despite significant strength values, the use of such design is associated with the need of an energy source and is most interesting for applying as active magnetic bearing.

This paper considers the passive superconducting elements with a “trapped” magnetic field made of HTS tape, which can be used similarly to bulk superconductors, both during cooling in an external magnetic field (FC) and in a zero magnetic field (ZFC). Currently, a large number of scientific publications in this area are devoted to experimental studies of the levitation properties of the such material using simple samples of HTS stacks as well as the processes of their magnetization [5-12]. Unlike bulk superconductors, structures made of HTS tape layers can be made of arbitrary shape with different directions of anisotropy, which allows expanding the possibilities for creating new topologies of magnetic systems for contactless magnetic suspensions.

In this work we study and compare the levitation properties of HTS bulks and a stack of HTS tape. The aim of the research is to analyse experimental results to compose and justify mathematical models for calculation magnetic system with such types of superconductor which will be used to development new magnetic system with HTS tape stacks. The paper presents the results of experimental measurements and of the force characteristics of HTS samples after FC and ZFC and «trapped» after cooling in magnetic field of permanent magnet, as well as calculations obtained with developed mathematical models for describing the properties of HTS bulks and stacks.

2. Method of calculation

For calculations of magnetic systems with high-temperature superconductors we use the homemade software for 3D analysis of an electromagnetic field, which is based on the numerical method of integral equations of electromagnetic field sources – EasyMag3D.

Due to nonlinear anisotropic properties HTS material accurate modelling of its properties in numerical calculation may cause difficulties, which especially appear in case of thin superconducting layers such as in a HTS stack.

In this paper we used two different ways to describe studied superconducting samples. For HTS bulks – the model of transport currents that represents electrical resistivity of HTS by a function of field parameters and temperature [13-15]

\[
\rho(H, J, T) = 0.5\rho_0 \times \left(1 + \tanh\left[-\left(1-T/T_C\right) \cdot \left(1 - \left|H/H_C(T)\right| \cdot \left(1 - \left|J/J_{c,max}(T, H)\right|/\delta_J\right)\right]\right),
\]

where \(\rho\) and \(\rho_0\) – the electrical resistivity in the superconducting and normal states respectively; \(J_{c,max}(T)\) – critical current density; \(T\) – temperature, \(H\) – magnetic field strength; \(H_C(T)\) – critical magnetic field strength, \(T_C\) – the critical temperature, \(\delta_J\) – constant coefficient of dispersion of the current density function.

The dependence of the critical current density on the magnetic field strength is determined by the power function

\[
J_c(T, H) = J_{c,max}(T) \cdot \left|H/H_C(T)\right|^2, \quad \text{when } |H| \leq H_C
\]

\[
J_c(T, H) = 0, \quad \text{when } |H| > H_C
\]

where \(J_{c,max}(T)\) – the maximum value of the critical current density at a given temperature. In is assumed that during experiment temperature of HTS does not change, hence the critical magnetic field strength \(H_C\) and maximum value of the critical current density \(J_{c,max}\) are constant, as well as first expression in brackets of tanh.

For modelling properties of HTS stacks the described model is not effective because of the need to take into account the distribution of induced currents in very thin superconducting layers. In such geometry this leads to a critical increase in the number of finite elements, as well as an increase in the error in solving equations.

However, due to the structure of HTS stacks, currents in the stack have vortex form and can be modelled as their magnetic moments. Thus, the distribution of the magnetic moments of the
superconducting currents in such structure can be represented with sufficient accuracy using nonlinear magnetization.

The ability to displace an external magnetic field by induced currents according to the Faraday law, in case of the magnetization is defined as

\[ \frac{dM}{dH} = -1. \]  

The critical current density is replaced by critical magnetization, which also depends on the parameters of magnetic field and temperature

\[ M_C(T, H) = M_{C_{\text{max}}}(T) \cdot [1 - \left( \frac{|H|}{H_{CM}(T)} \right)^2], \text{ when } |H| \leq H_{CM}(T) \]  

\[ M_C(T, H) = 0, \text{ when } |H| > H_{CM}(T) \]

where \( M_{C_{\text{max}}} \) – maximum critical magnetization, \( H_{CM} \) – critical magnetic field strength for magnetization.

Model of magnetization was used to describe the diamagnetic properties of bulk HTS materials in the combined model with two types of sources inside the volume of HTS. This mathematical model have shown good agreement with experimental results in previous works \[16,17\].

3. Studied HTS samples

Studies of levitation properties were carries out for three superconducting sample: two HTS bulks (in the forms of disk and ring) and s stack of 2G HTS tape.

HTS bulks were made of YBCO at Bauman Moscow State Technical University. Bulks have external aluminium casing for increasing hardness and protection during experiments. The studied samples are shown in figure 1 and dimensions of superconductors (without casing) are presented in table 1. Disk HTS has diameter 46 mm and height 7 mm. Ring HTS has outer diameter 46 mm, inner diameter 30 mm and height 7 mm.

Stack was composed of 20 layers of 2G HTS tape as shown in figure 2. We use 12 mm wide SuperOx tape with solder coating. Average critical current \( I_C \) of the tape is 300 A. Each layer consists of three tape segments. Segments are not overlapping and have the same length of 36 mm. Adjoining layers have alternate orientation (rotated 90 degrees). Stack is placed inside aluminium box with cover and fixed with screws to hold it during experiments. Result stack sizes – 36 × 36 × 2.4 mm.

![Figure 1. HTS bulks (disk and ring).](image)

![Figure 2. HTS stack: (a) – structure of layers; (b) – during assembly; (c) – finished look.](image)

| Parameter             | HTS disk | HTS ring |
|-----------------------|----------|----------|
| External diameter (mm)| 46       | 46       |
| Inner diameter (mm)   | –        | 30       |
| Height (mm)           | 7        | 7        |
4. Experiments
Experimental research of the HTS bulks and the stack includes the force measuring and the analysis of a «trapped» magnetic field, which were carried out on the special laboratory equipment. During all experiments we used liquid nitrogen for cooling the samples to temperature about 78 K.

4.1. Force measurements
Figure 3 shows the laboratory stand for measuring force characteristics of HTS samples. In this work, we measured the force interaction between the HTS samples and cylindrical permanent magnet with diameter 40 mm and height 20 mm. Magnetic induction of the magnet is 1.1 T. Permanent magnet is fixed on the shaft due to attractive force to steel disk at the end of the shaft. Shaft can be moved up and down by the stepping motor. To exclude influence of induced currents in aluminum parts, permanent magnet moves with a low speed of 0.5 mm/s.

HTS sample is fixed inside the cuvette for liquid nitrogen. Cuvette with the sample is placed on the weights, which are used to measure the force, as the difference between the values during experiments and the weight of cuvette (with the sample, nitrogen, and additional elements). Displacement of the permanent magnet (relative to the weights) is measured by the position sensor.

Experiment was carried out as follows. At first, the gap $\delta$ between the permanent magnet and HTS sample was installed at the cooling point. This point depends on the type of cooling mode – maximum gap at ZFC mode and minimum gap at FC mode. HTS sample was cooled using liquid nitrogen in a few minutes. After cooling the permanent magnet was moved vertically and the gap was changed. Force characteristics are measured as a dependence of the force acting on the HTS sample on the gap.

4.2. Trapped magnetic field
For experimental study of «trapped» magnetic field, the HTS sample was fixed inside cuvette and then cooled at FC mode (figure 4(a)). As a source of magnetic field, we used the same permanent magnet as for measuring the force, which was placed on the top of the sample in the way that the central point...
of the sample and permanent magnet coincided. After cooling permanent magnet was removed far from and HTS was saved a part of the initial magnetic field. This is a «trapped» magnetic field. Figure 4(b) shows how we measured this «trapped» magnetic field as the distribution of magnetic field above the surface of a superconductor. Hall Sensor was fixed at the start point (close to the border of HTS) and then moved along the central line of the sample. Step of measuring is 1 mm. To reduce friction it slid over a thick fluoropolymer film with thickness of 0.05 mm.

In the case of the HTS stack permanent magnet directly touch the surface of aluminum box with the stack of tapes inside. Because there is a wall of the box, the minimal gap for cooling is 2 mm. That values also is the minimal height to measure the distribution of magnetic field. When study the HTS bulks a non-magnetic insertion was placed between permanent magnet and superconductor to save the gap of 2 mm as for the HTS stack.

Figure 4. Experiment with «trapped» magnetic field: (a) – cooling; (b) – measuring. 1 – permanent magnet; 2 – cuvette with liquid nitrogen; 3 – superconductor; 4 - fluoropolymer film; 5 – Hall probe.

5. Results
Experimental measurements of the force between the permanent magnet and HTS samples were carried out for two cooling modes – Field Cooling (FC) and Zero F ield Cooling. «Trapped» magnetic field of HTS was measured for disk HTS and HTS stack at FC. After analysis of obtained data we simulated performed experiments and have defined parameters of the mathematical models of HTS properties described above. Result of calculations with defined parameters are compared with experimental dependencies and presented in this sections together.

5.1. Force characteristics
Figure 5 and figure 6 shows the results of force characteristics for HTS bulks after ZFC and FC. In the case of ZFC HTS bulk was cooled far from the permanent magnet (50 mm). After that permanent magnet was installed at the distance 25 mm (start point of the dependencies). Measuring of force and coordinates was performed during motion from that gap to the minimum gap ≈0.3-0.5 mm and backward. At FC HTS bulk was cooled at a distance 0.8 mm between superconductor and permanent magnet. Then the permanent magnet was moved up to the gap 20 mm and returned to the start point.

The same experiments were carried out for HTS stack. At ZFC the stack of tapes was cooled at a distance 50 mm from the permanent magnet. After cooling the permanent magnet was installed at the gap 35 mm and then moved down to the minimum gap ≈2.5 mm and backward. The value of minimal gap is defined by the thickness of the wall of aluminum box (2 mm) in which HTS stack is fixed. Results for HTS stack is shown in figure 7 as dependence of the force on the gap between permanent magnet and surface of HTS stack. Results for FC are presented in figure 8. First HTS stack was cooled at a distance 2.5 mm between permanent magnet and superconductor. After that permanent magnet was moved up to the gap 30 mm and then returned to the start point.
Calculation results, which are presented in figures, as mention above have been obtained after experimental measuring. Based on a comparison of experimental and calculated data, the parameters of critical current density, critical magnetization and critical magnetic field strength for current density and magnetization in (2) and (5) were found (table 2). Defined model parameters show good agreement with the results of experiments and can be used to simulate studied types of superconducting materials. To compare the levitation properties of HTS bulks and stacks we calculate the force dependence for equivalent HTS bulk, which has the same dimensions as considered stack of tapes. Calculated dependencies for ZFC and FC modes you can also see on figure 7 and figure 8.
Table 2. Defined model parameters for HTS material.

| Model of current density | Model of magnetization |
|--------------------------|------------------------|
| $J_{C,\text{max}}$       | $150 \text{ A/mm}^2$  |
| $H_C$                    | $2300 \text{ kA/m}$   |
| $M_{C,\text{max}}$       | $166666 \text{ kA/m}$ |
| $H_{CM}$                 | $2300 \text{ kA/m}$   |

The approximate value of model parameters $J_C$ and $H_C$ can be determined by characteristics $I_C(B)$ or $J_C(B)$, which are usually provided by the manufacturers of HTS materials. For magnetization model $M_{C,\text{max}}$ can be found from the critical current as a linear current density in the wall of superconducting layer. Note, that the critical current in the wall of superconducting layer is a half of critical current of the tape which is indicated in the specification (because current flow in both directions in cross section of the tape in HTS stack). $H_C$ of the HTS tape and $H_{CM}$ of the HTS stack are the same values.

5.2. Trapped magnetic field

Experimental measurements and results of calculation of the distribution of a magnetic field at a distance 2 mm above the surface of HTS samples after FC are shown in figure 8 for HTS disk and in figure 9 for HTS stack. Calculations of magnetic field were performed using model parameters, which were defined after studied force characteristics, and also show good agreement for HTS disk. Discrepancy between theoretical and experimental distributions of magnetic field maybe appears because in calculations the layers of HTS stack were modelled as a square $36 \times 36$ without separation of individual tapes. This assumption is also confirmed by the fact that the experimental dependence has the extremums at the centers of each tape in the nearest to the surface layer.

As for the forces, we compare the «trapped» magnetic field in HTS stack with calculation result for equivalent HTS bulk, which has the same dimensions as considered stack of tapes. Calculated dependence is shown in figure 9. The study of the «trapped» magnetic field allows us to identify differences in the levitation properties of the bulk superconductors and HTS stacks, which affect the force characteristics, i.e. the prime cause of the difference. Unlike bulk superconductors, in HTS stacks the extreme points of magnetic induction characteristic are observed above the centers of each tape because in this case each tape segment tries to save its part of the magnetic field. The maximum value of the «trapped» magnetic field in HTS stack is mostly limited by the properties of a single segment of the tape, while in a bulk superconductor – by the total current in the cross-section of the sample. Therefore, the trapped magnetic field in bulk superconductors is higher than in the HTS stacks, which leads to a similar difference in force characteristics. However, with an increase in the critical current of HTS tapes, the levitation properties of HTS stacks can exceed the parameters of bulk superconductors.
6. Conclusion
In this work, we have studied the properties of HTS bulks in form of a disk and a ring and an HTS stack made of 2G HTS tape. For both types of superconductor experimental measurements of the levitation force between a permanent magnet and HTS material are performed. Field Cooling (FC) and Zero Field Cooling (ZFC) processes are considered. Also, the distribution of a "trapped" magnetic field after cooling in an external magnetic field is studied.

Methods for modelling bulk HTS and HTS stacks are presented and results of its applying are shown by comparison with the experimental data. Proposed for HTS stack model of magnetization have shown a good agreement in force calculation, but has discrepancies in the form of «trapped» magnetic field. Calculated distribution of magnetic field does not show extreme points and does not take into account field heterogeneity. Generally, the method for modelling of HTS stack using magnetization was justified and this problem will be solved in future works.

Also as result, we obtained information about the features of HTS stacks, which are important for creating magnetic levitation and compare the levitation properties of HTS stack and equivalent HTS bulk with the same dimensions. Parameters of equivalent bulk were obtained from experimental studies of HTS bulk, thus the theoretical dependencies for equivalent HTS are accurate enough to comparison. Despite the fact that the considered HTS stack has shown lower characteristics than HTS bulks, its use can be effective in magnetic suspensions due to the absence of restrictions on the size and shape, as well as the constant increase in the maximum critical current of HTS tapes against the absence of changes in the properties of HTS bulks.

References
[1] Sass F, Sotelo G, Polasek A and Andrade R 2011 IEEE Trans. Appl. Supercond. 21 1511-14
[2] Martins F G R, Sass F, Ferreira A C and Andrade R 2018 IEEE Trans. Appl. Supercond. 28 6602405
[3] Pan Y, Wu W, Qiu D, Sheng J, Hong Z and Jin Z 2019 IEEE Trans. Appl. Supercond. 29 4700505
[4] Mukoyama S et al. 2017 IEEE Trans. Appl. Supercond. 27 3600804
[5] Patel A, Hopkins S C and Glowacki B A 2013 Supercond. Sci. Technol. 26 032001
[6] Patel A, Kalitka V, Hopkins S C, Baskys A, Alibetti A F, Giunchi G, Molodyk A and Glowacki B A 2016 IEEE Trans. Appl. Supercond. 26 3601305
[7] Patel A et al. 2017 Supercond. Sci. Technol. 30 024007
[8] Liu K, Yang W, Ma G, Quéval L, Gong T, Ye Ch, Li X and Luo Zh 2018 Supercond. Sci. Technol. 31 015013
[9] Li X, Yang W, Zhu J, Zhang H, Song D and Bai M 2019 IEEE Trans. Appl. Supercond. 29 4600405
[10] Osipov M, Abin D, Pokrovskii S and Rudnev I 2016 IEEE Trans. Appl. Supercond. 26 3601704
[11] Osipov M, Abin D, Pokrovskii S and Rudnev I 2017 IEEE Trans. Appl. Supercond. 27 3601504
[12] Sass F, Sotelo G G, Junior R D A and Frédéric S 2015 Supercond. Sci. Technol. 28 125012
[13] Dergachev P A, Kurbatova E P, Kurbatov P A and Kulaev Y V 2018 Rus. Electr. Engineer. 89 496-500.
[14] Kurbatova E 2018 IEEE Trans. Appl. Supercond. 28 5207704
[15] Dergachev P, Kosterin A, Kurbatova E and Kurbatov P 2016 Proceed. IEEE Intern. Power Electr. and Motion Contr. Conf. 574-579.
[16] Kulaev Y V, Kurbatov P A and Kurbatova E P 2017 Rus. Electr. Engineer. 88 465-470
[17] Kurbatova E, Kuschenko E, Sysoev M, Drozdov A, Dergachev P and Kurbatov P 2019 Proceed. 16th Conf. on Electrical Machines, Drives and Power Systems 1-4