Comparison of levitation forces of the cc-tapes stacks from different manufacturers

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Abstract. High-temperature superconductors (HTSC) have a significant potential for application in systems based on magnetic levitation. The wide spread of second-generation HTSC tapes (CC-tape from coated conductors) allows the use of stacks of CC-tapes as an alternative to bulk superconductors, particularly in levitation systems. The paper presents the results of research of CC-tapes of various manufacturers - SuNAM, THEVA and SuperOx. The tapes were cut into square 12 mm × 12 mm fragments and stacked in stacks, the number of tapes varying from 10 to 100. The measured dependences of the levitation force on the distance between the magnet and the stack have similar patterns for tapes of all manufacturers - the force of interaction increases with increasing thickness of stacks. However, the influence of the thickness of the stack on the levitation force for different CC-tapes is of a different nature.

1. Introduction
High-temperature superconductors (HTS) have the significant potential for magnetic-force-based applications. Currently, the widely used material in this application is bulk REBa2Cu3O7-x (REBCO, wherein RE corresponds to the rare earth elements). This material is capable of trapping magnetic fields and sustaining stable levitation a above a permanent magnet without active control. All of this opens up a wide range of applications: levitation bearings, maglev (magnetic levitation) trains, flywheel energy storage, motors and generators [1, 2]. However, wide spread of CC-tapes enables the use of HTS stacks as alternative to bulk superconductors. Using stacks of CC-tapes makes it possible to overcome some of the difficulties associated with the bulk drawbacks such as brittleness, low thermal conductivity.

Nowadays, researchers actively investigate the possibility of using HTS tapes in levitation applications. The stack, formed from pieces of industrial tape, is superior to the bulk superconductor on the tensile strength and thermal stability at low temperatures [3]. A detailed comparison of the advantages and disadvantages of stacks of tapes and bulk HTS for levitation applications is given in our previous work [4]. In our previous papers we studied the possibility of capturing the magnetic field by stacks of tapes [5, 6] and the levitation force of the stack of HTS tapes above the permanent magnet with respect to the lateral displacement, vibrations and crossed magnetic fields [4, 7, 8]. Also, we have studied the levitation force and trapped flux for various magnetizations of the stack [9]. For the development of an HTS bearing and transportation systems, it is important to predict the levitation performance of a stack of CC-tapes based on tape characteristics, such as critical current and engineering critical current density.
In our work we present new results on the vertical levitation force of HTS stacks of various thickness, from 10 to 100 tapes provided by different manufacturers: Theva, Sunam, SuperOx.

2. Experimental Techniques

2.1. Samples

Samples of different manufacturers were tested: Theva, Sunam, SuperOx. In the experiments on measuring the levitation force we used 12 mm wide tapes, coated with silver, without copper coating. The main characteristics of the tapes are presented in Table 1.

The Theva manufacturer provided two tapes with serial numbers 17617 and 17618, which are samples of the commercially produced TPL1100 tape. The minimum critical current of these tapes, measured by the manufacturer by use of TapeStar at 77K, self-field, are 360 and 518 A, the average critical current is 429 and 670. The substrate of the tapes consists of Hastelloy c276, 90-100 µm thick. The tape produced by Sunam has a substrate of similar thickness of about 100 microns, the substrate material is non-magnetic steel. The average critical current of the tape measured by the four-contact method is about 850 A. Tapes manufactured by SuperOx differ from all the above samples with a thinner substrate, and as a result, with thinner tapes and higher engineering current density. The average critical current of the tape is about 550 A according to the manufacturer specification.

| Tape     | Average critical current | Thickness of stack of 100 tapes, mm | Substrate                      |
|----------|--------------------------|-------------------------------------|--------------------------------|
| Theva 617| 429                      | 11                                  | Hastelloy C276 90 – 100 µm     |
| Theva 618| 670                      | 11                                  | Hastelloy C276 90 – 100 µm     |
| Sunam    | 850                      | 11.5                                | Non-magnetic SUS : thickness >80 µm |
| SuperOx  | 550                      | 5.5                                 | Hastelloy C276 40 – 50 µm      |

2.2. Experimental setup

Measurements of levitation force were conducted by use of home-made experimental setup. A basic experiment details can be found in [9]. A stack of CC-tapes was placed in a brass holder, which, in turn, is placed in a cryostat with liquid nitrogen (Fig.1a). The cryostat with the sample holder (4 on Fig.1b) was mounted on a motion system (1 on Fig.1) capable of vertical and lateral movements with a minimal step of 2 µm.

In our experiment we used a stack of four permanent magnets Nd-Fe-B (5 in Fig.1a) for supplying an applied magnetic field. Each magnet was 30 mm in diameter, 10 mm high, made of N45 grade material providing a surface remnant flux density of 0.30–0.33 T. The whole stack of magnets had a surface flux density of 0.58 T. The stacked magnets were placed on top of the load cell (6 in Fig. 1a) to measure the vertical levitation force.

All measurements were carried out in the zero field cooling mode. The stack was placed at a vertical distance of 80 mm away from the permanent magnet, where external magnetic field could be neglected. After that, the cryostat was filled with liquid nitrogen to cool the sample. Further, the sample was lowered down with a step of 0.5 mm with repulsive force measurements on each step. After that, the sample was lowered down in 0.5 mm steps with measurements of the repulsive force at each step. During measuring procedure, the sample displacement was stopped for 500 milliseconds on each movement step. The distance between the stack and the permanent magnets in the final position was 5.5 mm. The stray magnetic field provided by the stack of magnets at this distance was 0.35 T.
The sample was descended from an initial position to a test final position. The distance between the stack and the permanent magnets in the final position was 7 mm. At the final distance the sample was moved laterally in order to evaluate the effect of the lateral displacement on the repulsive or lateral forces. In field cooling (FC) mode, the sample was first descended to its final position, and then it was cooled by liquid nitrogen. Examples of descending curve measurements for stacks of 100 tapes are shown in Fig. 1b.

**Figure 1.** a) Experimental setup for levitation force measurements. 1 – motion system, 2 – cryostat, 3 – liquid nitrogen, 4 – brass holder, 5 – stack of Nd–Fe–B permanent magnets, 6 – load cell, 7 – stack of tapes.

b) The dependence of repulsive force $F_Z$ between the stack and the permanent magnet on the vertical coordinate $Z$ during descending of the stack. Results for stacks of 100 layers are shown. Legend displays the manufacturer of the tape. The temperature was 77 K.

3. Results and Discussion

From the descending curves in Fig. 1b, it is seen that samples of tapes with a higher critical current have a higher levitation force. A sample of SuperOx is standing out. Despite the lower critical current of the tapes compared to Sunam, SuperOx shows a comparable to Sunam levitation force. This can be explained by the smaller thickness of SuperOx tapes, which leads to higher values of the engineering current density. It also stands out that with the decrease in distance, and hence with the growth of the field, the differences between the tapes levitation force only increase. This may indicate that in higher fields it becomes more relevant to use CC-tapes with a higher critical current.

Let us consider in more detail the maximum repulsive force - the repulsive force measured at the minimum distance to the magnet. The dependence of this force on the number of tapes in the stack for different manufacturers is presented in Figure 2a. It can be seen from the figure that for the tapes of Sunam and Theva companies stacks of tapes with a higher critical current demonstrate higher levitation force. Although the critical current of the SuperOx tape is comparable to the Theva 618's critical current, the levitation force in this case is higher and comparable in magnitude to Sunam. This can be explained, as mentioned above, by the smaller thickness of SuperOx tapes, which leads to higher values of the engineering current density. It can be seen from the graphs that curves with a higher value of levitation force saturate faster. The difference in the levitation force at first increases with the number of tapes. However, for a higher number of tapes in the stack, the advantage of tapes with a higher critical current is reduced. Under the experimental conditions, it is most effective to use tapes with a higher critical current value for stacks of about 50-60 tapes.

Fig. 2b shows the dependence of the maximum repulsive force on the number of tapes in the stack normalized to the engineering density of the critical current in one tape (77K, self-field). It can be seen from the graphs that the curves for the samples of tapes produced by SuperOx and Theva coincide
well with each other. However, Sunam's tapes differ greatly in their levitation characteristics from other tapes. This suggests that the engineering current density of tapes can not be a universal factor that allows predicting the levitation properties of a stack of tapes. The difference in the behavior of stacks may be due to the difference in the type of pinning and is explained by the different dependancies of critical current on external magnetic field and on the angle between field and tape plane.

![Figure 2](image). a) The dependence maximal repulsive force on the number of tapes in the stack for different manufacturers. The measurement temperature was 77 K.

b) The dependence maximal repulsive force on the number of tapes in the stack for different manufacturers, normalized to the engineering density of the critical current in one tape (77K, self-field). The measurement temperature was 77 K.

4. Conclusions
We have carried out an investigation of the influence of the number of the elements in the stack on levitation force for stacks of 10–100 GdBCO tapes provided by different manufacturers. All measurements were performed in ZFC mode in liquid nitrogen. Based on the obtained results, we can conclude that:

1) As a rule, with increasing engineering current density in a single tape, the levitation force of a stack of CC-tapes increases.

2) The engineering current density of CC-tapes cannot be a universal factor that allows to accurately predict the levitation properties of a stack of tapes.

3) For large values of the engineering density of the critical current, the levitation force goes to saturation faster.

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