Non-additivity of magnetic levitation force

I A Rudnev and Yu S Ermolaev

Department of Superconductivity and Physics of Nanostructures,
Moscow Engineering Physics Institute (State University),
31 Kashirskoe Shosse, Moscow 115409 Russia

E-mail: rudnev@supercon.mephi.ru

Abstract. We present results of experimental measurements and numerical simulations of influence of superconductive block thickness on value of magnetic levitation force. It was found that dependency of magnetic levitation force on thickness of superconductive block is nonlinear both ZFC and FC conditions that means a non-additivity of levitation force.

1. Introduction

It has been well known that a permanent magnet PM can be stably levitated above a high-temperature superconductor (HTSC) cooled down to temperature of liquid nitrogen. The phenomenon of magnetic levitation results from the interaction of the induced current inside the superconductor with the inhomogeneous magnetic field generated by the PM. Owing to its possible technical and industrial applications, such as magnetic levitation transport systems [1], noncontacted superconducting bearings [2,3], gravimeters [4], flywheel energy storage systems [5-10], and motors [11] the magnetic levitation between a PM and an HTSC has been the subject of intensive studies for the last time. The most common peculiarity of the magnetic levitation is the hysteretic behavior of the vertical force \( F_z \) as a function of the distance \( z \) between the PM and the HTSC (frequently named as a levitation gap) when the PM is descending to and then ascending from the HTSC. When a PM approaches a zero-field-cooled HTSC, the levitation force increases monotonically from zero; demonstrating repulsion between superconductor and permanent magnet. As the PM is moving away from the HTSC, the levitation force decreases sharply to a negative peak at some distance, indicating attractive force between the HTSC and the PM, then declines to zero again at larger distance.

The important question which arises from levitation system design is an influence of superconductive block thickness on value of magnetic levitation force. This problem was studied theoretically, for example, in Ref. [12]. Now we present the results of experimental investigations and numerical simulations of HTS bulk thickness influence on vertical force \( F_z \).

2. Experiments

Seven single-domain YBCO bulk samples, with \( c \)-axis normal to the top surface of the sample, were used to investigate the effect of superconductor size on the levitation force. All disc-shaped samples have a diameter \( 2R=14 \text{ mm} \) and thickness \( b=2 \text{ mm} \). So we can to scale up the total size of superconductive block by a factor of seven. The trapped magnetic field and levitation force were nearly the same for all individual samples. A cylindrical permanent Nd-Fe-B magnet was used as a source of magnetic field. The size of the magnet was 25 mm in diameter and 13 mm in length. The magnetic field density at the centre of the top surface measured by a Hall probe was 0.3 T.
The levitation forces between samples and the magnet were measured under zero field-cooled (ZFC) and field-cooled (FC) states at $T=77$ K. The maximum levitation force measured in this experiment was taken at the smallest gap (2 mm) between the two nearest surfaces of the sample and the magnet.

3. Results and discussions

Figure 1 shows the dependencies of levitation force on levitation gap (distance between the YBCO sample and the magnet) in zero field-cooled (ZFC) state at 77 K. Similar curves were obtained for the cases when we used two, three and so on up to seven coaxial samples as blocks. From $F(z)$ curves we have extracted peak values of levitation (repulsive) forces. Figure 2 demonstrates the maximum repulsive force as a function of number $N$ of single samples. Top axis in Figure 2 is scaled in units of aspect ratio $b/2R$ of whole block. It can be seen from the figure that for small aspect ratio, the maximum repulsive force increases linearly with $b/2R$, but saturates as $b/2R$ is further increased. The

![Figure 1 Dependencies of levitation force on levitation gap for single sample (ZFC). Squares - experiment, solid lines – calculation by finite elements method. ZFC. The arrows mean the direction of magnet moving relative to superconductor: 1 – the first decrease of levitation gap; 2 – subsequent increase of levitation gap; 3 – second decrease of levitation gap. At further cyclic increasing and decreasing of levitation gap the value of levitation force will evaluated by the curves 2 and 3.]

![Figure 2. Dependence of peak levitation force on thickness of HTSC block. It is seen that $F(Z_s)$ has a linear behavior at small $Z_s$ and then possess a saturation.](image-url)
total levitation force is not equal to sum of forces from individual samples. In other words levitation force is a non-additive quantity. For technical applications, a superconducting disk with diameter $2R$ approximately equal to the thickness may be optimum for magnetic levitation, since further increase of the thickness will enhance the levitation force slightly.

To clarify the origin of saturation of maximum repulsive force as a function of number $N$ we have carried out numerical simulations both $F_z(z)$ dependencies and current profiles in HTSC blocks. Numerical simulations were performed by using the finite elements method in the frame of critical state model. The details of calculation were described in Ref. [13]. Results of simulation are presented in Figure 1 and Figure 2 as solid lines. We can see that the calculated data are consistent with the experimental observations. Current profiles for the cases of one, two, three and seven samples are presented in Figure 3. It seen that the current distributions are strongly un-uniform and saturated by current volume decreases with respect to whole superconductive volume as number of discs increases.

Figure 3. Calculated current profiles for different number individual samples $N$ in HTSC block. The saturated by current regions are marked by black color.
A similar result was obtained for the FC case. In Figure 4 maximum repulsion and maximum attractive forces are plotted as a function of number $N$.

4. Conclusion
We have presented results of experimental study of influence of superconductive block thickness on magnetic levitation force. In experiments, we have measured the dependencies of levitation force on levitation gap at step-by-step increase of thickness of superconductive block that was a set of seven coaxial discs of melt-textured YBCO. We have found a nonlinearity dependency of magnetic levitation force on thickness of superconductive block that means a non-additivity of force. To explain obtained data we have performed calculation both levitation force and current profiles into superconductive block by means of finite element method. It was established that the non-additivity of magnetic levitation force closely related with a change of volume distribution of critical current and, as a consequence, essential decrease of current saturated part of superconductive volume. Obtained results point to the possibility of essential reduction of superconductive materials in MagLev systems owing to optimization of the shape of bulk HTS.

Acknowledgment
We thank O Poluschenko and N Nizelskiy for preparation of the YBCO samples.
This work is supported by the Ministry of Education and Science of Russia.

References
[1] Wang J S, Wang S Y, Zeng Y W, Deng C Y, Ren Z Y, Wang X R, Song H H, Wang X Z, Zheng J and Zhao Y 2005 *Supercond. Sci. Technol.* **18** S215
[2] Hull J R, Hilton E F, Mulcahy T M, Yang Z J, Lockwood A and Strasik M 1995 *J. Appl. Phys.* **78** 6833
[3] Weinberger B R, Lynds L, Hull J R and Balachandran U 1991 *Appl. Phys. Lett.* **59** 1132
[4] Goodkind J M 1999 *Rev. Sci. Instrum.* **70** 4131
[5] Hull J R 2000 *Supercond. Sci. Technol.* **13** R1
[6] Hull J R, Mulcahy T M, Uherka K L, Erick R A and Abboud R G 1994 *Appl. Supercond.* **2** 449
[7] Kameno H, Miyagawa Y, Takahata R and Ueyama H 1999 *Appl. Supercond.* **9** 992.
[8] Bornemann H J, Ritter T, Urban C, Zaitsev O, Weber K and Rietschel H 1994 *IEEE Trans. Appl. Supercond.* **2** 439
[9] Chen Q Y, Xia Z, Ma K B, McMichael C K, Lamb M, Cooley R S, Fowler P C and Chu W. K. 1994 *Appl. Supercond.* **9** 457
[10] Coombs T A, Campbell A M, Ganney I, Lo W, Twardowski T and Dawson B 1998 *Mater. Sci. Eng. B* **53** 225
[11] Oswald B, Krone M, Soll M, Stresser T, Oswald J, Best K J, Gawalak W and Kovalev L 1999 *IEEE Trans. Appl. Supercond.* **9** 1201
[12] Qin M J, Li G, Liu H K, Dou S X and Brandt E H 2002 *Phys. Rev.* **B** **66** 024516
[13] Ermolaev Yu S, Rudnev I A 2005 *Technical Physics Letters* **31** No24 60