Suppression of magnetic levitation force in melt-textured \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \) superconductors by a transverse AC magnetic field

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Abstract. We have studied experimentally the influence of transverse ac magnetic fields on the levitation force arising between a permanent NdFeB magnet and a bulk melt-textured HTSC YBCO superconducting sample. The axes of superconducting disc and cylindrical magnet were coinciding while the transverse ac magnetic field generated by resistive coil was directed parallel to surface of a disc i.e., perpendicular to the disc axis. We found that application of both impulse and alternative transverse magnetic fields results in suppression of the value of levitation force and its relaxation rate. Namely, the variable magnetic field with amplitude 12 mT, that approximately in 20 times is less than field of a constant magnet, causes suppression of force more than twice. Monotonous behavior of value of levitation force reduction with the increase in transverse magnetic field amplitude was observed. The possible origin of observed phenomenon is discussed.

1. Introduction
The electrodynamics of hard superconductors is a very complex problem if the external magnetic field changes both its modulus and direction. This problem has drawn considerable attention from many research groups for a long time. A wide variety of interesting phenomena were discovered and interpreted on the basis of the developed concepts. One of them is the suppression of static magnetization and magnetic relaxation processes rate under the action of a transverse ac magnetic field. These phenomena were studied both theoretically and experimentally in detail in Ref. [1-5].

At the same time it is well know that there is a relation between magnetization of hard II type superconductors, in particular, a high-temperature superconductor (HTSC), and levitation force originating from interaction of permanent magnet (PM) and superconductor (see, for example, the results of our numerical calculations [6]). So, observed in [1-5] suppression of magnetization in transverse magnetic field should lead to reduce of levitation force too.

In the present paper we have checked this assumption and made sure that the both value of levitation force and the relaxation rate of levitation force are actually decreased significantly by the action of the transverse ac magnetic field. It is a very important result since superconductors undergo crossed ac and dc magnetic fields in many technical and industrial applications based on levitation phenomenon.
2. Experiments
Melt-textured YBa$_2$Cu$_3$O$_x$ (YBCO) disclike samples with diameter and thickness 14 mm and 2 mm accordingly were cut from bulk textured cylinders grown by the seeding technique. The homogeneity of samples was checked by a scanning Hall probe. The $c$ axis was perpendicular to the plate face of the sample. At $T=77$ K, the characteristic value of the magnetically measured critical current density $J_c$ in the ab plane is of the order of 9 kA/cm$^2$. The levitation force has been measured as a function of levitation gap (distance between permanent magnet top and bottom surface of sample) and time. An experimental setup was described in detail in Ref. [7]. External magnetic field was created by cylindrical permanent NdFeB magnet with size 12 mm and thickness 8 mm. The longitudinal axis of the superconducting disc was coinciding with that of the permanent magnet. The transverse ac magnetic field with frequencies $f=1$ Hz or 50 Hz and a single impulse were generated by resistive coil. An axis of resistive coil was directed parallel to the surface of disclike superconductors, i.e. perpendicular to the disc axis. Positional relationship between resistive coil and superconductors provided no thermal heating of superconductor. All measurements were performed at the liquid-nitrogen temperature $T=77$ K. The study of influence of transverse magnetic field on levitation force was carried out at constant levitation gap $h_g=2$ mm. The value of magnetic field at the magnet axis on $h_g=2$ mm was equal to 2.7 kOe.

3. Results and discussions
Figure 1 shows the typical dependencies of levitation force on distance between the YBCO sample and the magnet in zero field-cooled (ZFC) state at 77 K. 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 (levitation gap) when the PM is descending to and then ascending from the HTSC. When a PM approaches to 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.

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.

In the next experiments a zero-field-cooled sample was moved to the minimum gap 2 mm and the relaxation measurements were started. Then transverse magnetic field was turned on after relaxation of levitation force in a few seconds.
Figure 2 presents the changes in a value of levitation force under influence of single impulses of
transverse magnetic field with the magnitude $b_{tr} = 1.05$ kOe and the duration in a few seconds.

The beginning and ending of impulses are marked by arrows. It is well seen that the impulses of
transverse field lead to significant reduction of levitation force (more than 30 percent after first
impulse). The second and following impulses cause less pronounced change in levitation force $\Delta F_L$.

Note that a small relaxation with an increase in force was observed after magnetic impulses were
turned off. The value of $\Delta F_L$ for the first impulse is a monotonically increasing function of the value of
transverse magnetic field $b_{tr}$ as it is seen on Figure 3.

An alternative transverse magnetic fields make a more strong impact on levitation force than
impulse one. Namely, the switching on of ac transverse magnetic field with a frequency 50 Hz and
amplitude of 80 Oe (that more than 30 times less than the field of permanent magnet) have led to
levitation force reduction by a factor of 2.25 in 30 seconds (see Figure 4). One can see that relaxation
rate decreases too.
The physical origin of observed phenomena apparently connects with suppression by a transverse magnetic field of critical state in high textured YBCO bulk superconductor [1-5].

The influence of the crossed magnetic field would be larger if the superconductor is in the saturation state because the change in the magnetically induced currents will be large. Besides, superconductive sample has to have significance anisotropy, i.e. to be highly textured. The last one results in a striking difference in lengths of penetration of magnetic field in different directions. It means that if superconductor is isotropic or its size is too large (out of saturation state), one expects that the suppression of levitation force by alternative transverse magnetic field will be less pronounced.

4. Conclusion

In conclusion, we have presented novel results of experimental study of influence of transverse variable magnetic field on value of magnetic levitation force. We have found a drastic decrease in value of levitation force and its relaxation rate under action of an additional transverse magnetic field. Monotonous behavior of value of levitation force reduction with the increase in ac magnetic field amplitude was seen. Observed phenomenon may be explained based on the concept of suppression of critical state in anisotropic bulk HTSC superconductors. The received results can be strictly important for designing of MagLev systems.

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