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FACTORS AFFECTING CHARACTERIZATION OF BULK HIGH-TEMPERATURE SUPERCONDUCTORS*

by

John R. Hull,
Energy Technology Division, Argonne National Laboratory
9700 South Cass Avenue, Argonne, Illinois 60439

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FACTORS AFFECTING CHARACTERIZATION OF BULK HIGH-TEMPERATURE SUPERCONDUCTORS

JOHN R. HULL

Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439 USA

ABSTRACT

Three major factors affect the characterization of bulk high-temperature superconductors in terms of their levitation properties during interaction with permanent magnets. First, the appropriate parameter for the permanent magnet is internal magnetization, not the value of the magnetic field measured at the magnet's surface. Second, although levitation force grows with superconductor thickness and surface area, for a given permanent magnet size, comparison of levitation force between samples is meaningful when minimum values are assigned to the superconductor size parameters. Finally, the effect of force creep must be considered when time-averaging the force measurements. In addition to levitational force, the coefficient of friction of a levitated rotating permanent magnet may be used to characterize the superconductor.

KEY WORDS

levitation, bulk characterization, force measurements, superconducting bearings

INTRODUCTION

Bulk high-temperature superconductors (HTSs) are used in applications such as fault current limiters and current leads that are essentially wire applications. The standard methods under development for HTS wire characterization can probably be used directly to characterize bulk HTSs for these applications. Bulk HTSs can be used in other applications, e.g., magnetic bearings, vibration dampers, etc., for which there is no wire analog. Characterization methods specific to these applications are in a rudimentary stage of development. This paper discusses factors that affect the characterization of bulk HTSs with specific reference to magnetic bearing applications.

LEVITATION FORCE MEASUREMENTS

Most HTS bearings consist of a permanent magnet (PM) levitated above a bulk HTS. Thus, it is not surprising that one of the most prevalent characterizations of bulk HTS is the measurement of levitation force between a PM and the HTS. The

force is often measured by a strain-gauge transducer connected to the PM. The distance is often inferred by the movement of the stage carrying the PM and force transducer plus the deflection of the transducer, which can be calculated from its mechanical stiffness. Alternatively, the position may be detected directly, e.g., by some optical method.

In a typical measurement, the HTS is held stationary in a bath of liquid nitrogen and allowed to cool long enough that the sample is at uniform temperature throughout. The HTS is cooled with the PM in air at some fixed distance. The PM is then brought toward the surface of the HTS and the repulsive levitation force is measured at various heights until the PM reaches some height close to the surface. The PM is then made to move away from the surface, and during this part of the traverse the PM may experience an attractive force. The traverse process may be repeated while the sample is still cold to obtain additional hysteresis loops. Minor hysteresis loops consisting of small-distance reversals may be made during a major loop. The initial descent almost always has a larger force than any of the subsequent descents, although the force measurements during a second descent will be essentially repeated during a third and any

subsequent descents. Similarly, the first ascent is repeated in second and subsequent ascents.

One would like to obtain a single number that characterizes the levitation force. One must then choose a height at which to measure this force. It was determined early in the study of bulk HTS that the force versus height on the descent part of the hysteresis loop has an exponential dependence [1], as shown in Fig. 1, over the last several mm of a descent. Thus, it is possible to interpolate a set of measurements to any height or extrapolate the force to the HTS surface. In practice, it is difficult to measure the levitation force at small heights, because if the HTS is in a liquid-nitrogen bath and liquid covers the surface of the HTS, then the liquid may attach to the PM and the surface tension of the liquid may affect the measurement. One could immerse the entire PM part of the system in liquid nitrogen, but this adds to the cost of performing the measurement, and is not needed if the extrapolation technique is used. Alternatively, one could mount the HTS onto a cold head of a refrigerator, but there would then be a thermal gradient through the HTS. As shown below, extrapolation to zero height appears to be preferred, because it eliminates many of the geometric dependences in the choice of PM.

Comparing samples from different laboratories is usually confounded by the use of different PMs in different places. One may transport the same magnet from laboratory to laboratory to serve as a standardization, but this seems impractical for large sets of measurements. The author believes that it is sufficient to report the magnetization of the PM, as indicated in Fig. 1. Any additional components contributing to the magnetic field seen by the HTS, such as a soft-magnetic keeper, should also be reported. The magnetic dipole moment of the PM assembly is useful but not essential information. The magnetic dipole moment of the PM may be measured by rotating the PM at the center of a Helmholtz coil pair. The average internal magnetization can then be calculated by dividing by the volume of the PM.

The magnetization of a PM is temperature dependent. Usually the magnetization increases as temperature decreases, although FeBNd PMs have a maximum in magnetization at about 140 K. It is important to keep the PM temperature within some range during the measurements and to report this range. It is the practice in the author's laboratory to keep the PM at approximately room temperature. Keeping the PM at liquid-nitrogen temperature is also an option.

Another possible figure of merit for the levitation force measurement is the ratio of the force between the PM and HTS divided by the levitation force between the PM and its mirror image. The latter number would be the result obtained if the HTS were an infinite half-plane and had an infinite current density, i.e., the perfect diamagnetic case. A ratio of 1.0 is the maximum theoretically obtainable in this simple system. If one has a pair of identical PMs and can measure the force between them, then the PM/HTS measurement should be compared to this.

One may calculate analytically the repulsion force between a pair of cuboidal PMs using the method of Akoun and Yonnet [2]. In this calculation one assumes there is no demagnetization, i.e., $\mu_r = 1.00$, where μ_r is the relative magnetic permeability of the PM. With modern PMs, μ_r can be 1.05 or lower, so this is a reasonable approximation. The calculation consists of a sum of 256 simple terms. One may numerically integrate a large number of cuboidal results to obtain the results for cylindrical shapes, e.g., bounding the cylinder by a set of inscribed and circumscribed cuboids and taking the average.

Fig. 2 shows the results of levitation pressure versus separation gap between two coaxial cuboidal PMs, calculated by the method of Akoun and Yonnet [2] for different sized magnets. As can be seen from Fig. 2, the levitation pressure is the same at zero gap, independent of the size of the permanent magnets. Similar results hold for cylindrical PMs. The levitation pressure P at zero height is given by

$$P = M^2 / (2\mu_0) \quad (1)$$

where μ_0 is the permeability of free space and M is the magnetization of the magnet. A magnetization of 1.0 T, produces a levitation pressure of about 398 kPa. Levitation pressure is defined in this paper as the levitation force divided by the bottom surface area of the PM.

One occasionally sees the attempt to predict the pure diamagnetic levitation pressure by measuring the magnetic field of the PM close to its surface and then taking some constant times the square of the field as the levitation pressure. For example, in a long aspect ratio PM the field measured at the surface is

approximately half the internal magnetization, and one might ascribe the proportionality as

$$P = 2 B^2 / \mu_0 \quad (2)$$

Fig. 3 shows the results of such a calculation [2] with the magnetic field determined at the center of a PM at three different heights, and compares it to the exact analytic calculation by the method of Akoun and Yonnet [2]. Apparently, the use of Eq. (2) starts to introduce sizable differences at aspect ratios $L/W < 1$. Further, the result is sensitive to the actual height at which the measurement of the magnetic field is made. A measurement at a height equivalent to $Z/W = 0.1$ will significantly underestimate the levitation force of a pure diamagnetic system, and overestimate the performance of the HTS. If a 1-cm-wide PM is used, then one would need to measure at a height of 10 μm in order to obtain $Z/W = 0.001$ and good accuracy for high aspect ratio PMs. This height is much smaller than the thickness of most commercially available magnetic field sensors. One could, of course, measure the magnetic field and then use a calibration curve similar to those shown in Fig. 3 to obtain the maximum force expected.

DIMENSIONAL EFFECTS

A basic question in characterization of bulk HTS is what size PM is appropriate. A large aspect ratio (tall) PM gives a higher levitation pressure than a small aspect ratio PM. A larger diameter PM gives a larger force than a smaller diameter PM, but the levitation pressures in the pure diamagnetic case are the same for the same aspect ratio. It is not clear what the effect of PM diameter has on the levitation pressure in the PM/HTS interaction when finite critical current density is assumed. Studies in this area (e.g., [3]) are far from definitive. One might hypothesize that because the average magnetization M_{HTS} of the HTS is given by

$$M_{\text{HTS}} = A J_c R \quad (3)$$

where A is a geometric coefficient, J_c is the critical current density, and R is the HTS radius, that a larger diameter PM would give a higher M_{HTS} and a higher levitation pressure. To the author's knowledge no theoretical or experimental studies have been devoted to this specific topic.

It has been known for some time [4] that for very thin HTS samples with the same PM that the force is proportional to thickness, but as the thickness increases the force reaches an asymptotic limit.

Assuming that J_c remains constant, it is reasonable to assume that for a given PM that levitation force will increase with HTS diameter. However, beyond some diameter, say two times the PM diameter, the increase is small. Perhaps the best recommendation for PM and HTS size is to choose values that are characteristic of those used in actual bearing designs.

FORCE CREEP

Associated with the phenomena of flux creep is the presence of force creep [5]. Force creep, which is characterized by a decay logarithmic in time, can greatly confound the legitimacy of force measurements. Clearly, if a very rapid traverse is made, the levitation force will be higher than if a slow scan is used. It is the practice in the author's laboratory to hold the PM at some fixed height and average the force over approximately 1000 measurements occurring over a time

period of several seconds. A second average is taken over a successive time period of equal length. If the difference between averages is less than the rms noise during a time period, the measurement is recorded and the PM moved to a new height. Otherwise, the averaging continues.

ROTATIONAL DRAG

One could also characterize an HTS by the rotational drag it produces on a standard PM, while the PM rotates at some speed and some height above the HTS. To a first approximation, the hysteresis energy loss E_h for such a system is

$$E_h = K (\Delta B)^3 / J_c \quad (4)$$

where K is a geometric constant and ΔB is the difference between minimum and maximum field values applied to the HTS as the PM rotates. For a standard PM, E_h , as evidenced by the rotational deceleration should be inversely proportional to J_c .

Difficulties with this method include the need to conduct the measurement in a vacuum for accurate results, difficulty in reproducing the levitation height for different HTSs, and the difficulty of obtaining PMs with similar inhomogeneities in different laboratories. Despite these difficulties, the rotational drag characterization may be more meaningful for bearing applications than ac susceptibility measurements, which typically apply a uniform ac field over the entire HTS surface.

CONCLUSIONS

In a levitation force measurement the appropriate parameter for the PM is internal magnetization, not the value of the magnetic field measured at the magnet's surface. For a given PM size, comparison of levitation force between samples is meaningful when minimum values are assigned to the HTS size parameters, e.g. the diameter of the HTS should be at least twice the diameter of the PM. Force creep must be considered when time-averaging the force measurements. In addition to levitational force, the rotational deceleration of a levitated rotating permanent magnet is proposed to characterize the HTS.

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Fig. 1 Levitation force versus height during initial descent of several HTS samples with standardized PM. The force extrapolated to zero height, F_0 , is provided for each sample.

Fig. 2 Analytic calculations of levitation pressure between two identical cubic permanent magnets magnetized at 1.0 T with length dimensions of a , b , c .

Fig. 3 Levitation force ratio of levitation force divided by force for an infinitely long PM versus the length to width ratio of the PM. The ratio calculated by the analytical method of Akoun and Yonnet [2] is compared to the force predicted by Eq. (2) with the magnetic field measured at a height z divided by the width w of the PM.

Fig. 1

Fig. 2

Fig. 3