

Simple Calibration Free Method to Measure AC Magnetic Moment and Losses

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Abstract - A calibration-free method to measure components of ac magnetic moment vector in a transverse ac magnetic field have been developed. This method is intended for studies of the ac vector magnetization and losses in HTS tapes, wires and long slabs at low temperatures. The method is suitable for measurement of samples carrying transport current. The advantages of the method, besides its vector character, are an extremely compact ac field excitation coil and the pick-up coil positioned outside of the excitation coil. Finite dimensions of the sample and of pick-up coils are taken into account. To illustrate the potential of the method, measurements of Bi2223/Ag tapes at 77 K were performed. The ac field amplitude 2 to 100 mT, the frequencies 20 to 230 Hz and various orientations of the ac field transverse to the sample plane were used. The dc magnetization and hysteresis losses of the samples were also measured. The observed dependence of the ac magnetic moment on the angle between the ac field direction and the superconductor plane is consistent with the conception of the "Geometrical locking of the irreversible magnetic moment to the normal of a thin-plate superconductor" (A.A. Zhukov et al. 1997 *Phys. Rev. B* 56 2809-2819).

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I. INTRODUCTION

The development of different methods to measure losses in superconductors has a long history. Additional attention to these was stimulated by the ITER design. Therefore, an international standard CEI IEC 61788-8 "Total AC loss measurement of Cu/Nb-Ti composite superconducting wires exposed to a transverse alternating magnetic field by a pickup coil method" has been accepted recently [1]. It is clear that the total losses involve the hysteresis losses in superconducting filaments and the losses due to coupling between filaments as well. Designs of different large-scale applications of high- T_c generate efforts to modify existing measurement methods with the aim to take into account the current anisotropy of high- T_c materials of the first and the second generations.

Between a number of different methods of ac loss measurement in superconductors under the action of the external magnetic field changing in time, the most popular and widespread methods are PVM (the Poynting vector method) [2], OTSP (a one-turn coil method with spiral loop) [3], LPVT (a linked pickup coil method with spiral loop) [4], SIM (a simple electromagnetic method) [5], SPC (a saddle type pickup coil method) [6], and CPC (the standard concentric pickup coil method) [1]. A comparative study of different methods of total ac loss measurements for superconducting oxide tapes is discussed in [7].

The difficulty of measuring losses in an anisotropic superconducting tape resides in a very strong dependence of a spatial magnetic field distribution on the direction of the

exciting magnetic field with respect to the tape. To obtain the necessary accuracy, the size of the pick-up coil has to significantly exceed sample size in all the methods mentioned above. This influences the measurement accuracy at low amplitude of the ac field and its small inclination to the tape plane. Therefore, one should select a compromise size of the pick-up coil and introduce a calibrating form factor. Moreover, the accuracy of methods using the pick-up coil is limited by imperfection of the coil generating ac field. The signal of the peak-up coil contains not only the component connected with the sample, but also the signal of the stray field of the ac magnetic flux of the inducing coil.

A new very simple and compact coil configuration is proposed. It allows one to perform an absolute measurement of the components of the tape magnetic moment and of losses in a wide range of audio frequencies. The width of the exciting coil is very close to the tape width. Within the framework of the dipole approximation, the proposed method allows one to measure the magnetization vector and losses in the tape without any additional calibration procedure.

II. THEORY

Electromagnetic losses Q in magnetic materials can be expressed through the whole magnetic moment \vec{M} acquired by the sample in the external magnetic field \vec{H}_e , as,

$$Q = -\overline{\vec{M} \frac{d\vec{H}_e}{dt}}, \quad (1)$$

where the upper horizontal line symbolizes time averaging. If \vec{M} and \vec{H} are proportional to $\exp(-i\omega t)$, expression (1) can be rewritten in the complex form,

$$Q = -\frac{1}{2} \operatorname{Re}(i\omega \vec{M} \vec{H}_e^*). \quad (2)$$

where the sign $*$ means a complex conjugation.

The components of magnetic moment \vec{M} are the linear functions of the external magnetic field,

$$M_i = V \alpha_{ik} (H_e)_k, \quad (3)$$

where the dimensionless value $\alpha_{ik}(\omega) = \alpha'_{ik} + i\alpha''$ is the dynamic magnetic susceptibility of the sample. The vector of the magnetic moment in the dipole approximation can be defined from the measurement of the magnetic field \vec{H} created by the sample. Such an approach can be applied in the case of a uniform sample of regular form and allows one to simplify calculations. The magnetic dipole situated in the origin of coordinates generates, in the point of observation characterized by the radius vector \vec{R}_0 , the magnetic field,

$$\vec{H} = \frac{3\vec{n}(\vec{M}\vec{n}) - \vec{M}}{R_0^3}, \quad (4)$$

where \vec{n} is a unit vector along \vec{R}_0 .

In what follows let us assume that the external uniform magnetic field \vec{H}_e is oriented along the z axis, the y axis is directed along the tape length L , and the normal to the tape plane is inclined with respect to the z axis by the angle φ . The tape dimensions (thickness a , width b , and length L) satisfy the following inequalities, $a, b \ll R_0 \ll L$. The magnetic field components H_x and H_z are connected with the corresponding

components of the 2D dipole moment m_x and m_z per unit length by the following equations,

$$H_x = 2 \int_0^{\infty} \left(3m_x \frac{x_0^2}{x_0^2 + y^2} - m_x \right) \frac{dy}{(x_0^2 + y^2)^{3/2}} = \frac{2m_x}{x_0^2}, \quad (5)$$

$$H_z = -2m_z \int_0^{\infty} \frac{dy}{(x_0^2 + y^2)^{3/2}} = -\frac{2m_z}{x_0^2}. \quad (6)$$

In the chosen geometry, the external magnetic field \vec{H}_e has only the component $(H_e)_z$. In compliance with Eq. (1), the electromagnetic losses Q are determined by the z component of the dipole moment only.

Therefore, to measure losses in a superconducting tape it is sufficient to define the z component of the magnetic moment m_z of the tape in the dipole approximation. Moreover, the measurement of both component m_x and m_z allows one to obtain the whole information about the magnetization vector of the tape.

III. RESULTS AND DISCUSSION

A scheme of the device for measuring ac losses within the framework of a proposed method is shown in Figures 1 and 2

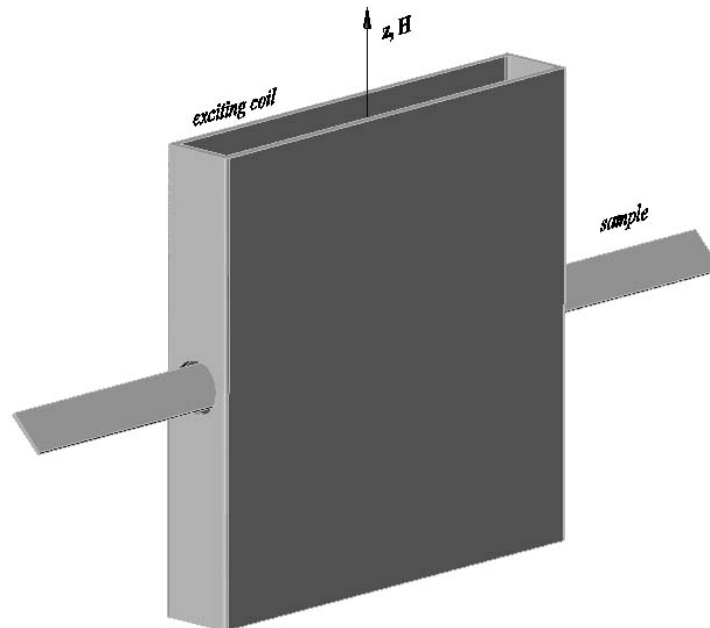


Fig. 1. The sample position in the developed device.

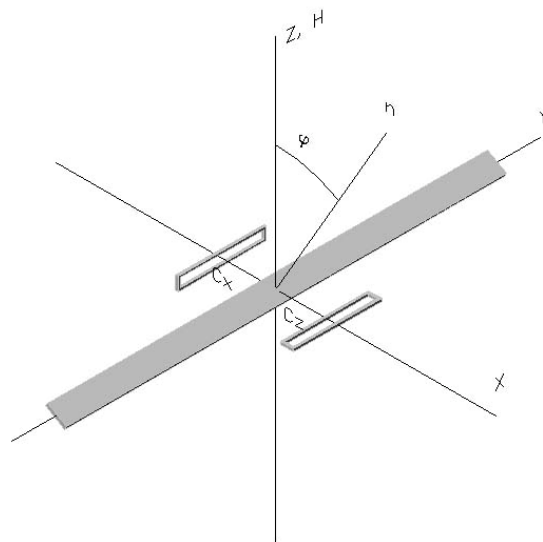


Fig. 2. The position of the tape in the coil generating the ac magnetic field and arrangement of the pick-up coils.

The size of the coil generating the ac magnetic field is $8 \times 60 \times 60 \text{ mm}^3$. It is wound using a copper wire about $40 \text{ }\mu\text{m}$ in diameter. Two pick-up coils are used to measure both components of the tape magnetic moment m_x and m_z . A working capacity of the device was checked by measuring the eddy current losses in a cylindrical copper sample 2.4 mm in diameter and 100 mm in length with a resistivity $\rho = 2.11 \cdot 10^{-7} \text{ Ohm cm}$ at the liquid nitrogen temperature and frequency $f = 73 \text{ Hz}$. The results of the loss measurement agree with a direct calculation of losses within about 3%.

Some results of the measurement of loss in Bi-2223/Ag tape of the first generation are shown in Figures 3 and 4. This tape, 100 mm in length, is characterized by the critical current of about 70 A and penetration field of about 20 mT at $T = 77 \text{ K}$.

The ratio of losses in the perpendicular and parallel ac fields with respect to the tape are shown to be about the ratio of the tape width to its thickness. We found that the angular dependence of losses is proportional to $\cos(\varphi)$ in a wide range of φ at a high enough ac field amplitude $B_0 < B_p$ where φ is the angle between \mathbf{B} and the normal $\mathbf{n} \parallel \mathbf{z}$ to the tape plane. These data reflect an interesting phenomenon of geometrical locking of the irreversible magnetic moment to the normal of a thin-plate superconductor [8].

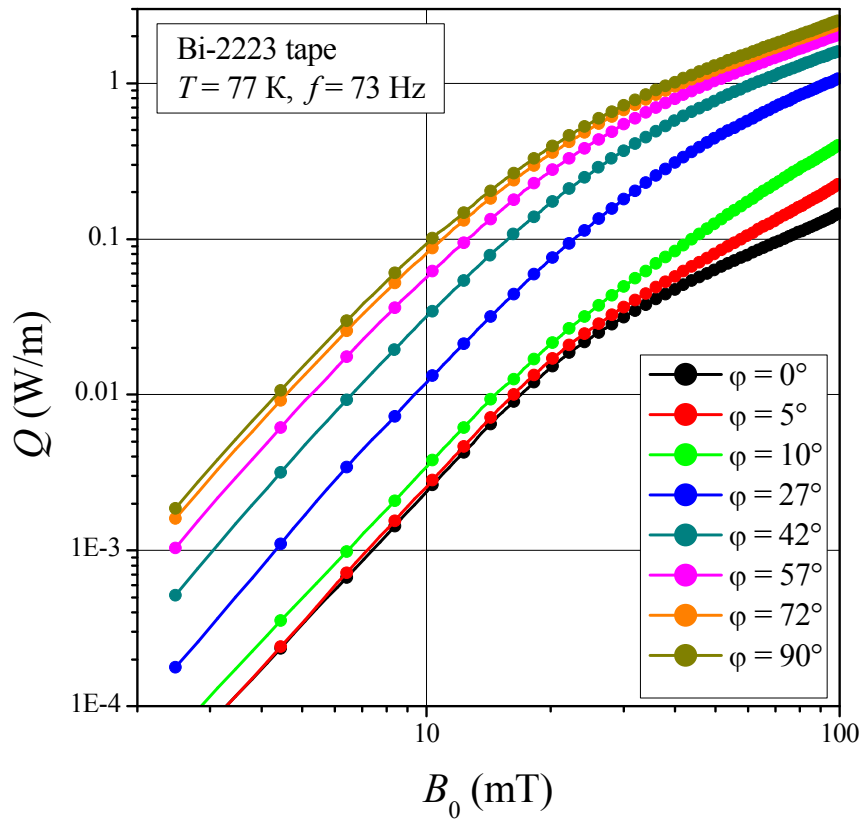


Fig. 3. The dependence of tape losses Q on the ac magnetic induction amplitude B_0 for different orientation of B_0 with respect to the tape plane.

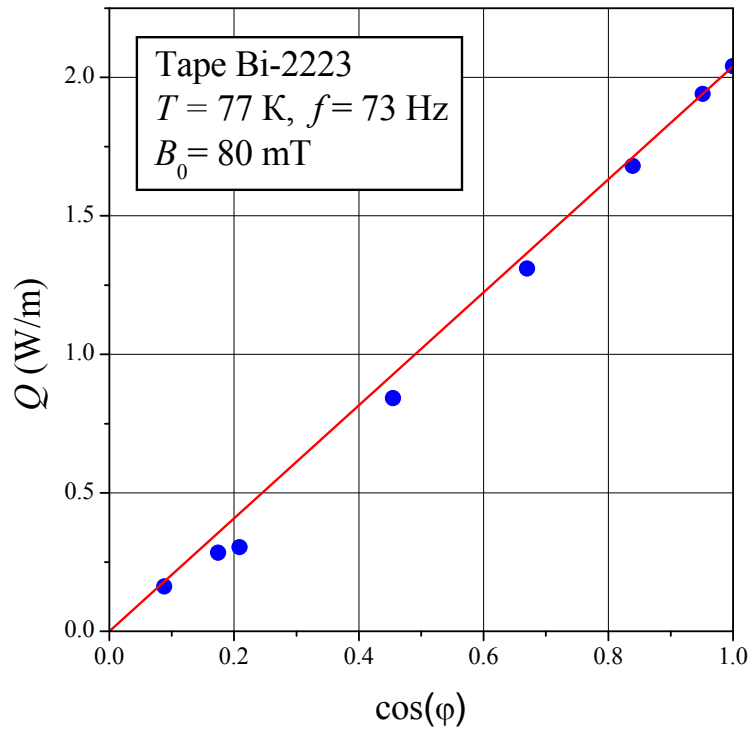


Fig. 4. The dependence of losses Q on $\cos(\varphi)$ at $B_0 = 80 \text{ mT}$ where φ is the angle between \mathbf{B} and the normal to the tape plane.

IV. CONCLUSION

The standard method (CPC) to measure the ac losses in superconductors is modified. The proposed version of the method is based on the dipole approximation. The method allows one to obtain information not only about the ac losses but to determine the value and orientation of the sample magnetic moment as well. The performed measurements demonstrated the effectiveness of the constructed device. The measurements of superconducting tapes show that the magnetization vector of the tape is oriented perpendicular to the tape plane

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