

Shielding and Losses in Multifilamentary Tapes Exposed to Perpendicular AC Magnetic Fields

Stefania Farinon, Pasquale Fabbriatore, Fedor G6m6ry and Eugen Seiler

Abstract—In multifilamentary High- T_C tapes for energy transportation, a component of magnetic field is applied normally to the filament surfaces. Since the thickness of any filament of the tape is much smaller than the width (the factor is usually between 10 and 20), it results in large field amplification on the tape surface and consequently a large loss. This problem is studied in detail here, analysing the behavior of Bi-2223/Ag tapes with different structure of filamentary zone. Experimental data are compared with calculations based on Finite Element Codes. Importance of filament arrangement for AC losses is illustrated.

Index Terms—ac losses, finite element analysis, High- T_C superconductor, multifilamentary tapes.

I. INTRODUCTION

High- T_C superconducting multifilamentary tapes are, for the time being, serious candidates for applications in electrical energy transportation. One of the main tasks of the conductor design is to minimize the ac dissipations due to the cyclic variations of the electrical and magnetic fields. Our attention is focused on that case, when the sample does not carry any transport current and is exposed to a perpendicular external magnetic field, i.e. that applied in the direction normal to the wide face of the superconducting tape. In general, the ac dissipation per unit volume in a harmonic external field $\mathbf{B} = B_0 \cos \omega t$ can be written as the loop integral of the magnetization \mathbf{M} with respect to the applied field

$$W = \frac{1}{\mu_0} \oint_{\text{cycle}} \mathbf{M} d\mathbf{B}, \quad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m. Introducing the complex ac susceptibility $\chi = \chi_0(\chi' - i\chi'')$, the ac losses can be expressed as

$$W = \pi \chi'' \chi_0 \frac{B_0^2}{\mu_0}, \quad (2)$$

where χ'' is the imaginary part of the ac susceptibility (called the internal susceptibility) and χ_0 is the external susceptibility under conditions of perfect screening, when the superconducting filaments are in the Meissner, state taken with negative sign. For a long cylindrical sample, placed in a

parallel magnetic field, $\chi_0 \sim 1$, so the losses are completely determined by χ'' , which in that case ranges from 0 to 0.25. As the cylinder length becomes smaller and smaller, down to values comparable with the radius, χ_0 increases to values larger than unity. As the cylinder approaches a thin disk we find $\chi_0 \gg 1$, while the χ'' peak is still around 0.25. In the literature this topic has been largely discussed and analytical expressions have been found for regular shapes such as rectangular strips, wires and infinite arrays of strips [1-5].

When dealing with real multifilamentary tapes exposed to a perpendicular oscillating field, although a significant literature does exist [6-7], several problems remain open. In [8-9] we reported some attempts to calculate the ac losses, in terms of χ_0 and χ'' , of real multifilamentary tapes, and then to compare the results with measurements. Particularly we proposed to apply standard numerical technique to this kind of problems, using the commercially available finite element code ANSYS [10]. We demonstrated that, although we do not have a specific theory for the critical state of multifilamentary tapes in a perpendicular field, it is possible to apply the theories developed for a single strip or disc, showing that a wide band of shielding current distributions is described by the disc (or strip) approach. This conclusion focuses the ac losses problem on the determination of χ_0 , which acts as an important scaling factor for the losses.

II. THE SUPERCONDUCTING TAPES

In this paper we will refer to six particular tapes, shown in Fig. 1. They are BSSCO-based tapes with one or more superconducting cores inserted in a silver matrix, manufactured at the Institute of Electrical Engineering of the Slovak Academy of Science [11-13]. The critical current density J_C at 77 K and no applied field for the tapes is shown in Table I, along with other relevant parameters.

TABLE I
THE MAIN CHARACTERISTICS OF THE SIX TAPES

	Tape width (mm)	Tape thickness (mm)	Fill factor (%)	J_C @ 77 K, and no applied field (A/mm ²)
(a)	1.8	0.31	36	52
(b)	2.5	0.14	18	100
(c)	2.5	0.20	16	50
(d)	3.9	0.27	32.5	82
(e)	3.8	0.28	39	162
(f)	2.2	0.55	39	28

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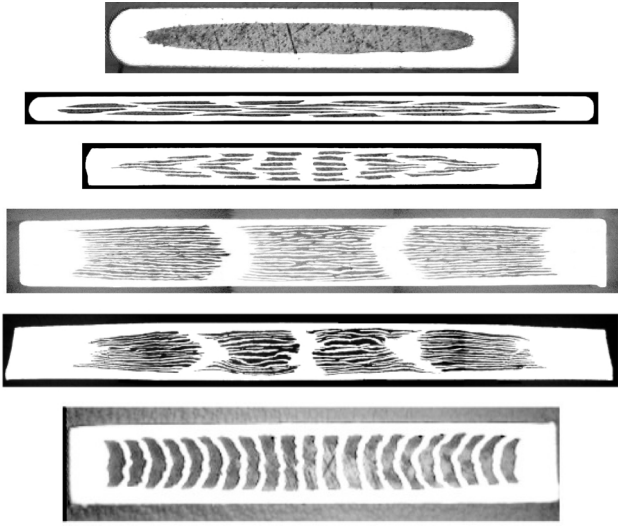


Fig. 1. Cross sections of the monofilamentary tape (a), the 19-filament tape (b), the 36-filament tape (c), the 60-filament tape (d), the 80-filament tape (e) and the 21-filament tape (f).

III. EXTERNAL SUSCEPTIBILITY

A. Calculations and measurements

In our previous work [8], we investigated the possibility to predict the external susceptibility χ_0 both analytically and numerically, demonstrating that commercially available finite element codes for magnetostatic problems can be applied to describe the Meissner shielding in superconductors. We tested our approach in the shapes derived from a thin rotational ellipsoid, for which analytical solutions are available, then we applied it to complex system like multifilamentary tapes.

Table II contains a summary of the analytical expressions for χ_0 , which can be applied to real conductors. The limit of these expressions is the regularity of the lattice of filaments. Fig. 1 shows that (apart tape a) which is monofilamentary) only tapes

d) and e) have a regular structure. Tape f) is anomalous in this frame; we have included it only for comparison. However, when dealing with real multifilamentary tapes, the only way to calculate the value of χ_0 is to use numerical codes. Fig. 2 shows how the external field is shielded by the six tapes taken under consideration according to ANSYS calculations. Then, the value of χ_0 comes out in a very straightforward way; considering the energy variation ΔW of a body with given magnetization M placed in a field B , χ_0 is given by:

$$\chi_0 = \frac{\Delta W}{(1/2\mu_0)B_0^2 V_{\text{sample}}}, \quad (3)$$

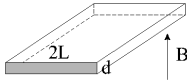
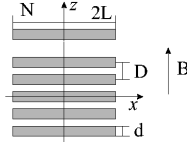
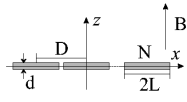
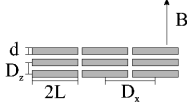
where V_{sample} is the volume occupied by the magnetized body.

In [10] we demonstrated that, if the sample volume is known, χ_0 is a physically measurable quantity. It is important to mention that, at experimental determination of χ_0 , both the field amplitude and the frequency should be low enough to guarantee that the field is shielded by the surface currents on each flat filament composing the tape.

In Table III a comparison between the measured values of χ_0 and the ones calculated by ANSYS and by using the empirical formulae is shown for the six tapes under consideration. The finite element calculations agree fairly well with the measurements (within 10%). Among the empirical formulae, the rectangular strip model applied to the filament bundle gives the best approximations, but it fails when applied to tape b), since in that case a half-filled central zone exhibits the same shielding as the tape were bulk.

It should be noticed that in the case of z-stacks with a large number of filaments (tapes d and e), it is not important their discretization, but the overall barrier they offer to the field. Actually, subdividing the tape (e) in its correct number of filaments the resulting value of χ_0 is 14.2, to be compared with 14.4 coming from the previous calculation. Fig. 3 shows an enlargement of the resulting flux lines; the field does not

TABLE II
EXPRESSION OF χ_0

Sample	External susceptibility
Rectangular strip 	$\chi_0 = \frac{\pi L}{2d}$
Finite z-stack 	$\chi_0(N) = \chi_{0,z\text{-stack}}(\infty) + \frac{\chi_0(1) - \chi_{0,z\text{-stack}}(\infty)}{N^{0.8}}$ where $\chi_0(1) = \frac{\pi L}{2d}$ and $\chi_{0,z\text{-stack}}(\infty) = \frac{D^2}{\pi L d} \ln \left[\cosh \left(\frac{\pi L}{D} \right) \right]$
Finite x-array 	$\chi_0(N) = \chi_0(1) \left[1 + \frac{2}{\pi} (\beta - 1) \operatorname{arcsec} \left(\frac{N + \Omega - 1}{\Omega} \right) \right]$ where $\beta = \frac{\chi_{0,x\text{-array}}(\infty)}{\chi_0(1)}$, $\Omega = 5\beta$ and $\chi_{0,x\text{-array}}(\infty) = -\frac{D^2}{\pi L d} \ln \left[\cos \left(\frac{\pi L}{D} \right) \right]$
xz-matrix ($n_x \times n_z$ tapes) 	$\chi_0 = \frac{\pi L f_x}{2 d f_z}$, where: $f_x = 1 + \frac{2}{\pi} (\beta - 1) \operatorname{arcsec} \left(\frac{n_x + \Omega - 1}{\Omega} \right)$ and $f_z = \frac{\chi_0(1)}{\chi_{0,z\text{-stack}}(\infty) + \frac{\chi_0(1) - \chi_{0,z\text{-stack}}(\infty)}{n_z^{0.8}}}$

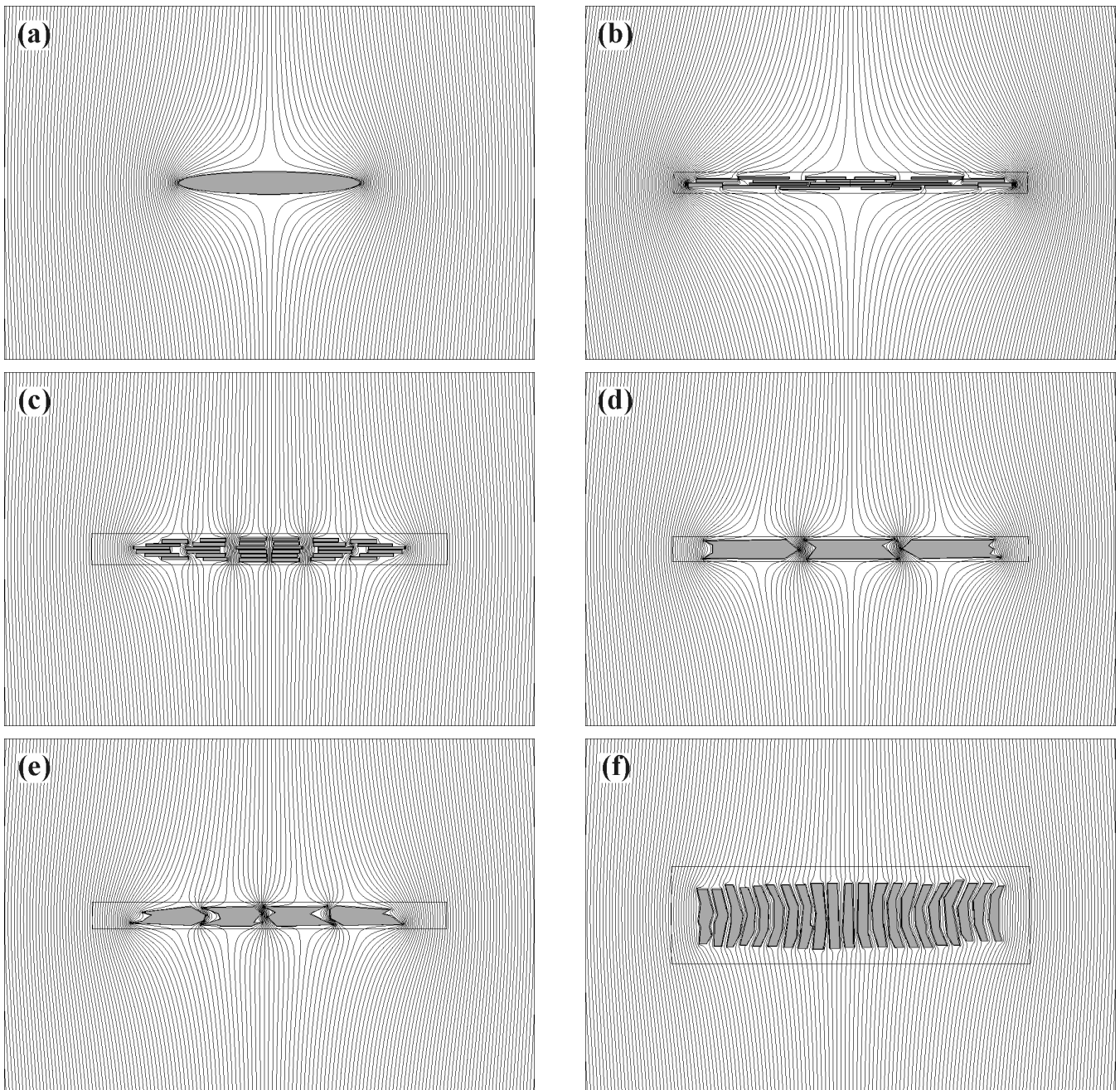


Fig. 2. Flux lines for the monofilamentary tape (a), the 19-filament tape (b), the 36-filament tape (c), the 60-filament tape (d), the 80-filament tape (e) and the 21-filament tape (f).

penetrate the inter-filament regions, but it is shielded by the filaments as they were a unique body.

B. Dependence on sample length

The numerical results given in Table III were obtained solving the two-dimensional (2D) field distributions, i.e. assuming the tape length is infinite. Main reason is practical: three-dimensional (3D) calculations require much more time or offer much less dense mesh than 2D ones, with severe consequences on precision. To test the validity of 2D approach we performed the experimental determination of χ_0 on pieces of different length cut from the same tape. A mono-

core tape with elliptical cross-section similar to the tape a) was chosen for this purpose. The experimental procedure described in [9] was used to find χ_0 for each piece. The results are given in Fig. 4. Data scatter for samples shorter than 1 mm can be explained by inevitable error in determination of sample volume at such small dimensions. At increasing the sample length, the importance of flux penetration from sample ends – that is not included in 2D calculations – diminishes and the shielding due to longitudinal currents dominates more and more. Important is that, for the sample length larger than 5 mm, the results seem to saturate. Thus, we conclude that the χ_0 results obtained on our samples with typical length of 6 mm can be reliably compared with the results of 2D calculations.

TABLE III
COMPARISON BETWEEN MEASURED AND CALCULATED χ_0

Tape	Measured χ_0	χ_0 calculated by ANSYS	Percentage difference (%)	χ_0 as calculated from the strip model applied to single filament	χ_0 as calculated from the strip model applied to filament bundle	χ_0 as calculated from the xz-array model
(a)	8.9±0.4	9.6	7.9	6.7	-	-
(b)	68.7±2.6	64.2	-6.6	25.1	24.1	-
(c)	13.7±0.8	14.9	8.8	16.5	13.0	6.9
(d)	12.8±0.6	13.8	7.8	100.1	10.7	12.6
(e)	15.1±0.8	14.4	-4.6	52.0	9.9	6.3
(f)	3.5±0.4	3.2	-8.6	-	3.8	-

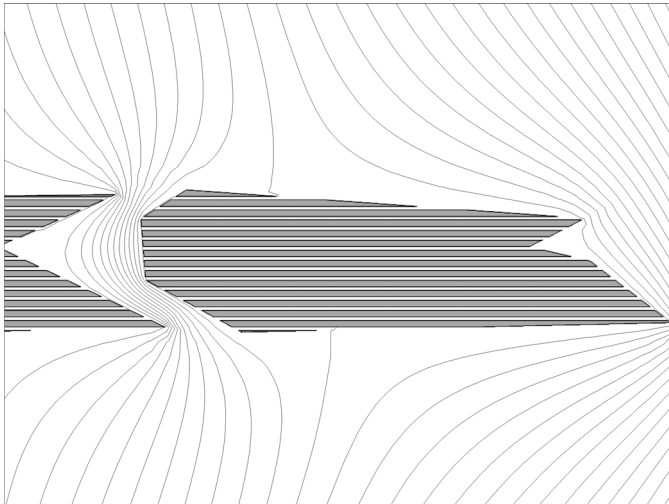


Fig. 3. Flux lines for the tape (e) obtained by modeling the 20×4 filaments.

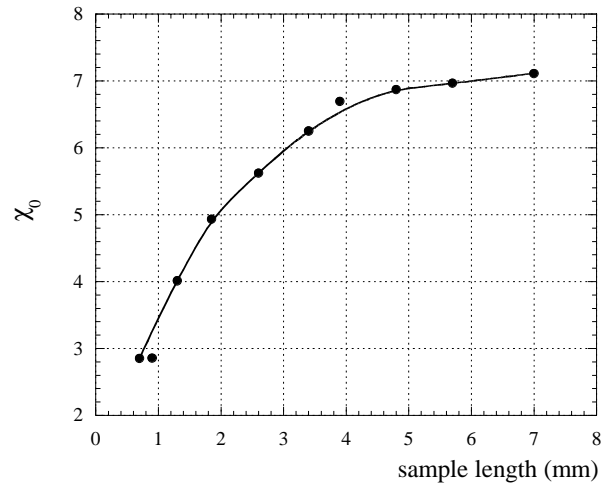


Fig. 4. χ_0 as function of the sample length for a mono-core tape.

IV. CONCLUSIONS

Significance of filament arrangement on the distribution of shielding currents and AC losses in multifilamentary tapes was investigated. When the magnetic field is applied perpendicularly to the tape wide face, its value at the filament edges is enhanced. The external susceptibility in diamagnetic state, χ_0 , is a good measure of this effect that directly influences the AC loss. We demonstrated that the commercially available finite element code ANSYS is suitable to compute this fundamental characteristic, examining tapes with different types of filamentary structure. The use of two-dimensional calculations was justified by experimental observation: the end effects become significant for samples much shorter than 6 mm, the typical length used in our experiments. From our study follows that the arrangement of filaments could dramatically influence the external susceptibility in diamagnetic state and thus the losses in perpendicular AC magnetic field.

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