Magnetothermal modeling of multilayer HTS tapes for their control at room temperature

Walid Dirahoui, Hocine Menana, Melika Hinaje and Jean Leveque
Université de Lorraine, GREEN
F-54000 Nancy, France
name.surname@univ-lorraine.fr

***Abstract*—This paper presents a 3-D magnetothermal modeling approach for the structural control of the high temperature superconducting (HTS) tapes at room temperature. A model based on an integro-differential formulation in terms of the electric vector potential is developed for eddy current computation in the HTS tapes; associated to a thermal modeling using the finite difference method. Numerical results are compared to experimental data for validation purposes. A rotating magnet wheel is used as inductor to avoid the thermal disturbance of current supplied inductors. The source magnetic field is calculated using the magnetic surface charge model.**

Keywords—HTS tapes, Eddy currents thermography, Integral Modeling, Measurements, Quality control, Rotating magnet wheel inductor.

I. Introduction

REBCO second generation (2G) high temperature superconducting (HTS) tapes present superior characteristics under magnetic field tapes, which make them promising for electric power applications. However, due to their specific manufacturing processes, 2G HTS tapes may present inhomogeneities and defects which may degrade their performances. Thus, non-destructive characterization for the investigation of inhomogeneities and defects, is crucial for quality control of such tapes at their manufacturing process. Several field mapping techniques, such as magneto-scan [1] and scanning Hall probe [2], have been successfully used for the control of the superconducting performances of long length HTS tapes. These techniques allow to characterize only the superconducting layer of the tapes at cryogenic temperatures. However, the other layers of the 2G HTS tapes, may also present structural defects, like delamination, which will weaken their thermal and mechanical performances, increasing the likelihood of hot spots appearing, leading to quenches even bellow the critical thresholds.

In this work, the use of eddy current thermography (ECT) at room temperature for the control of structural defects in 2G HTS tapes, is studied numerically and experimentally. Indeed, ECT is a promising technique that has been successfully applied to inspect thin and complex structures such as carbon fiber reinforced plastic (CFRP) [3]. An innovative inductor structure, based on a rotating magnet wheel, has been developed for the control of HTS tapes by ECT. A 3-D magnetothermal modeling approach is proposed where an integro-differential formulation in terms of the electric vector potential is developed for eddy current computation in the HTS tape which is subjected to a time-varying external magnetic field generated by rotating magnet wheel, combined with a thermal model based on finite difference method.

II. Experimental Setup

The experimental setup for the magnetothermal control at room temperature is shown in Fig. 1. It consists of a REBCO HTS, subjected to a time varying magnetic field generated by a rotating magnet wheel. The latter is composed of 20 north-south alternating magnetic poles. This structure of inductor is developed to avoid the heating disturbance which is unavoidable when using coils-based inductors. The magnetic field produced by the magnet wheel generates eddy currents resulting in heating of the HTS tape by Joule effect. Using an infrared camera, we collect and analyze the thermal map on the surface of the tested sample. The copper-based HTS tape surface presents, however, a low thermal emissivity, which may compromise the accuracy of the temperature measurement. The emissivity has significantly improved by adding a matt surface thin film on the HTS tape.

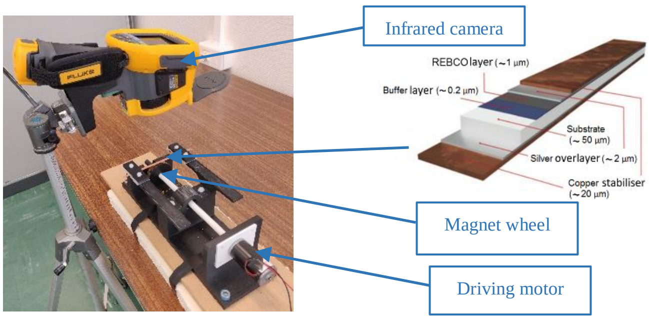

Fig. 1. The experimental setup.

III. Modeling Approach

The modeled system, in Cartesian coordinates, shown in Fig. 2, consists of an 2G HTS tape submitted to an external magnetic field generated by a rotating magnetic wheel in $y-z$ plane. Given the thin structure of the HTS tape, only the z component of the source magnetic-flux density $\vec{B}_z^s$ is considered. The eddy currents supposed to flow in the $x-y$ plane, are modeled by using an integro-differential formulation, involving only the normal component ($\vec{T}_z$) of the electric vector potential (Eq. 1) [4].

$$\vec{\nabla}\times\bar{\bar{\sigma}}^{-1}\,\vec{\nabla}\times\vec{T}_z = -\partial_t\left(\vec{B}_z^s + \frac{\mu_0}{4\pi}\int_v \frac{\vec{\nabla}\times\vec{T}_z\times\vec{r}}{r^3}\,dv\right) \qquad (1)$$

In (1), $\bar{\bar{\sigma}}$ and μ_0 are, respectively, the electrical conductivity matrix and the vacuum permeability. The Magnetic Surface Charge Model [5] is used to compute the source magnetic-flux density produced by the rotating wheel, given by (2).

$$\vec{B}_z^s = \frac{B^r}{4\pi}\sum_{i=0}^{1}\sum_{j=0}^{1}\sum_{k=0}^{1}(-1)^{i+j+k}\,atan2(ST,RU)\,\vec{e}_z \qquad (2)$$

where B^r is the remanent magnetization of the permanent magnets and atan2 is a four-quadrant arctangent function. The relative coordinates are given by

$$\begin{cases} S = x - (-1)^i a \\ T = (y + R_m sin\theta) - (-1)^j a \\ U = (z - R_m cos\theta) - (-1)^k a \\ R = \sqrt{S^2 + T^2 + U^2} \end{cases} \tag{3}$$

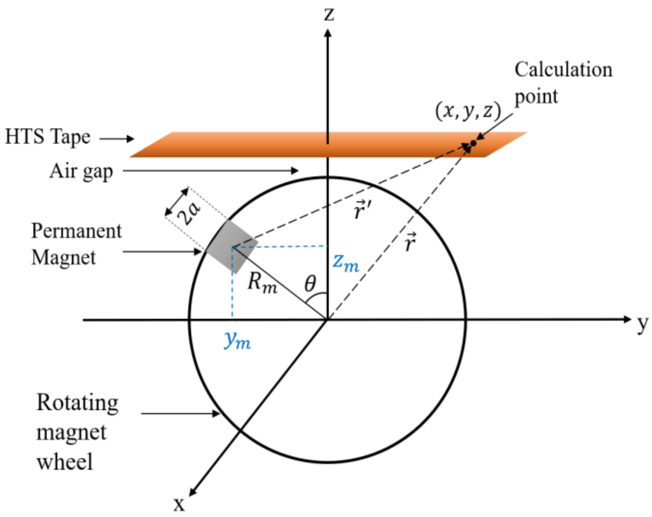

Fig. 2. The modeled system.

In (3), a represents the half of the cubic magnets edge length, R_m is the distance between the centers of the wheel and the magnets, as illustrated in Fig. 2, where (x, y, z) and (x_m, y_m, z_m) represents, respectively, the coordinates of the calculation point and that of the center of a magnet. The frequency of the magnetic field is linked to the rotating speed (Ω) of the wheel: $\theta = \Omega t$, where t is the time.

The thermal phenomena that occur in the tape, due to the Joule losses ($\mathcal{P}$), are governed by the heat diffusion equation, given by (4), where, λ, γ, Cp, h, Te, Γ and $\vec{n}$ are, respectively, the thermal conductivity, the mass density, the specific heat capacity, the convection exchange coefficient, the temperature of the surrounding medium, the surface of the tape and the vector normal to the tape surface. For the numerical analysis, (4) is discretized using the finite difference method.

$$\begin{cases} \gamma C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + \mathcal{P} \\ -\lambda \vec{\nabla} \mathrm{T}.\vec{\mathrm{n}} = h(T - T_e), \; on \; \Gamma \end{cases} \tag{4}$$

To reduce the computation time, a homogenization strategy is adopted in the thermal modeling, where the layers of similar (of the same order) thermal properties are assembled together. The copper and silver layers are thus assimilated to one layer named (Cu-Ag), and the YBCO and Hastelloy layers are assimilated to one layer named (Hast-YBCO). Buffer layers are omitted since they do not significantly influence the electromagnetic and thermal behavior of the tape. Because of the small gap (1.65 mm) between the inductor and the HTS tape, the rotation of the wheel imposes a forced cooling on the lower surface of the latter. We have considered this constraint by adapting the value of the convection coefficients.

IV. Results and Discussions

To check the validity of the modeling approach, the results are compared to experimental data. The values of parameters used in the simulation are given in Table I.

TABLE I. System Specifications.

Parameter	***Value***	***Description***
$L \mid W \mid T$	50 | 4 | 0.1 mm	Tape dimensions
γ_{Cu-Ag}	9112 kg/m^3	Cu-Ag mass density
$\gamma_{Hast-YBCO}$	8845 kg/m^3	Hast-YBCO mass density
λ_{Cu-Ag}	389 W/(m·K)	Thermal conductivity of Cu-Ag
$\lambda_{Hast-YBCO}$	10 W/(m·K)	Thermal conductivity of Hast-YBCO
Cp_{Cu-Ag}	371 J/(kg·K)	Specific heat of Cu-Ag
$Cp_{Hast-YBCO}$	424 J/(kg·K)	Specific heat of Hast-YBCO
h_x , h_y	5 W/(m^2·K)	Convection exchange coefficient along the x and y directions
h_z^S	80 W/(m^2·K)	Convection exchange coefficients at the lower surface in the z direction
h_z^N	15 W/(m^2·K)	Convection exchange coefficients at the upper surface in the z direction
B^r	1.4 T	Remanent magnetization of magnets
Ω	826.73 rad/s	Angular speed of the magnet wheel

Figure 3 shows a qualitative comparison between the simulation (Fig. 3(a)) and the experimental data (Fig. 3(b)), on the thermal mapping in terms of the temperature rise (ΔT) at the steady state. A good agreement is obtained between the measurements, performed by the infrared camera, and the simulation results. More results concerning a quantitative comparison for several wheel speeds, will be presented in the extended paper.

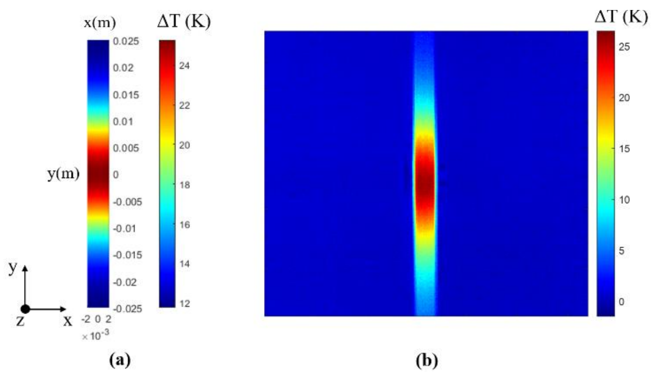

Fig. 3. Thermal mapping of ΔT: (a) Simulation, (b) Measurements.

References

[1] M. Zehetmayer, R. Fuger, F. Hengstberger, *et al.*, "Modified magnetoscan technique for assessing inhomogeneities in the current flow of coated conductors – Theory and experiment," *Physica C: Supercond. Appl.*, vol. 460–462, pp. 158-161, Sep. 2007.

[2] M. Carrera, J. Amoros, X. Granados, *et al.*, "Computation of Current Distribution in YBCO Tapes With Defects Obtained From Hall Magnetic Mapping by Inverse Problem Solution," *IEEE Trans. Appl. Supercond*., vol. 21, no. 3, pp. 3408-3412, June 2011.

[3] H. K. Bui, G. Wasselynck, D. Trichet, B. Ramdane, G. Berthiau and J. Fouladgar, "3-D Modeling of Thermo Inductive Non Destructive Testing Method Applied to Multilayer Composite," in IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 1949-1952, May 2013.

[4] H. Menana and M. Féliachi, "An Integro-Differential Model for 3-D Eddy Current Computation in Carbon Fiber Reinforced Polymer Composites," in IEEE Transactions on Magnetics, vol. 47, no. 4, pp. 756-763, April 2011.

[5] G. Akoun and J.-P. Yonnet, "3D analytical calculation of the forces exerted between two cuboidal magnets," in IEEE Transactions on Magnetics, vol. 20, no. 5, pp. 1962-1964, September 1984.