Characterization of Electrical Conductivity of Anisotropic CFRP Materials by means of Induction Thermography Technique

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Numerical simulations by means of finite elements are used to investigate the capacities of the induction thermography technique for the characterization of electrical conductivities of unidirectional Carbon Fiber Reinforced Polymer (CFRP) materials. A coupled electromagnetic-thermal model is presented using hexahedral elements to deal with thin region of fully anisotropic physical properties. Eddy-current problem is solved using the $T-\Omega$ formulation to deduce heat source density power. Transient thermal problem is solved with fixed time step. Experimental measurements are carried out to validate the approach.

***Index Terms*—Induction thermography, CFRP, Electrical conductivity characterization, coupled model.**

I. Introduction

STRATIFIED Carbon Fiber Reinforced Polymer (CFRP) materials have been widely used in aerospace to replace metals in structural components due to their light weight and excellent and configurable mechanical properties.

Because of their conception, these materials have strongly anisotropic physical properties. In terms of electrical conductivity, since carbon fibers are good conductors, CFRP composites have a good conductivity in the direction of carbon fibers but a very poor conductivity in perpendicular directions. The low conductivity may cause problems in practical applications, for example in induction welding of these materials or in electromagnetic shielding. The conductivities in different directions depend on the filling rate of carbon fibers, the manufacturing process and also the presence of flaws.

The characterization of the electrical conductivities of CFRP helps to improve their properties. In the literature, some non-contact techniques based on electromagnetic effects have been proposed to characterize the electrical conductivities of this kind of material. Eddy-current methods are classical ones with working frequency range up to some MHz [1][2][3]. Tetrahertz frequency technique has been presented which requires, however, a complicated and expensive system [4]. Microwave probe pumping techniques [5][6] is also a promising technique which uses microwave frequencies. These techniques generally use a scanning process and suffer from the low signal to noise ratio (SNR) due to the spread of induced field in the strong anisotropic medium.

In this paper, a new method based on induction thermography technique [7][8][9] is proposed in order to characterize the electrical conductivities of anisotropic materials. Because of the strong dependency of inductive electromagnetic power density distribution on the anisotropy ratio, the temperature image (the thermal effect of electromagnetic phenomena recorded by the infrared thermal camera) can be used to better observe the dispersion of induced electromagnetic field in the anisotropic material. A coupled and fully anisotropic electromagnetic-thermal model is developed to simulate the process. This model is based on hexahedral elements to model thin regions of anisotropic physical properties [10]. Eddy-current problem is solved using the $T-\Omega$ formulation as a fast numerical model.

The section II presents the technique used. The numerical model is introduced in the section III and IV. Simulation results are shown in the section V.

II. Induction thermography technique

Fig. 1 shows an induction thermography testing setup. The specimen is heated by means of an U-shaped coil which is fed by an induction generator via an impedance adaptation circuit. The specimen is heated up to $20°C$ above the ambient temperature. The time evolution of the temperature on the surface of the specimen is then recorded. It will be shown that the necessary heating duration and the pattern of temperature images depend strongly on the anisotropy ratio of the material.

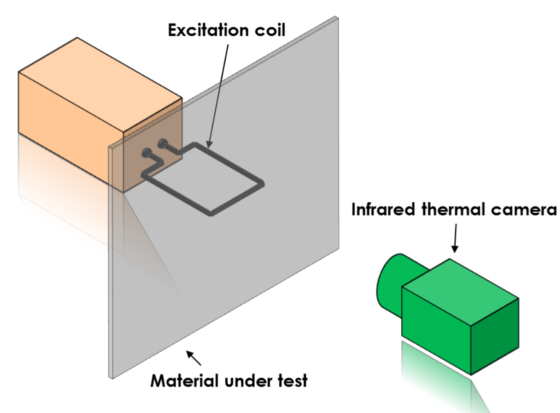


Fig. 1. Induction thermography setup.

III. $T-\Omega$ formulation for anisotropic materials

The matrix form of the discrete $T-\Omega$ formulation for fully anisotropic material reads:

$$(\mathbf{R}^t\mathbf{M}_{ff}^{[\rho^e]}\mathbf{R} + j\omega\mathbf{M}_{ee}^{[\mu]})\boldsymbol{T}_e - j\omega\mathbf{M}_{ee}^{[\mu]}\mathbf{G}\Omega_n = -j\omega\mathbf{M}_{ee}^{[\mu]}\boldsymbol{H}_e^s \quad (1)$$

$$-j\omega\mathbf{G}^t\mathbf{M}_{ee}^{[\mu]}\boldsymbol{T}_e + j\omega\mathbf{G}^t\mathbf{M}_{ee}^{[\mu]}\mathbf{G}\Omega_n = j\omega\mathbf{G}^t\mathbf{M}_{ee}^{[\mu]}\boldsymbol{H}_e^s \quad (2)$$

where **R**, **G** are respectively the discrete counterparts of *rot*, and *grad* operators, $\boldsymbol{T}_e = \sum_{i=1}^{E} \mathbf{w}^{e_i} \boldsymbol{T}_e^i$, $\Omega_n = \sum_{i=1}^{N} w^{n_i} \Omega_n^i$ and $\boldsymbol{H}_e^s$ the circulations of the magnetic source field $\boldsymbol{H}^s$ calculated on the edges of the mesh. The components of the matrix $\mathbf{M}_{ff}^{[\rho^e]}$, $\mathbf{M}_{ee}^{[\mu]}$ are given as follows:

$$\mathbf{M}_{ff}^{[\rho^e]}(i,j) = \sum_k \int_{V_e^k} ((\mathbf{w}^{f_i})^t [\rho^e] \mathbf{w}^{f_j}) dV \quad (3)$$

$$\mathbf{M}_{ee}^{[\mu]}(i,j) = \sum_k \int_{V_e^k} ((\mathbf{w}^{e_i})^t [\mu] \mathbf{w}^{e_i}) dV \quad (4)$$

where facet shape functions and edge shape functions are denotes as $\mathbf{w}^f$ and $\mathbf{w}^e$ respectively. The electrical resistivity tensor $[\rho^e]$ and the permeability tensor $[\mu]$ are represented as:

$$[\rho^e] = \begin{pmatrix} \rho_{xx}^e & \rho_{xy}^e & \rho_{xz}^e \\ \rho_{yx}^e & \rho_{yy}^e & \rho_{yz}^e \\ \rho_{zx}^e & \rho_{zy}^e & \rho_{zz}^e \end{pmatrix}, \quad [\mu] = \begin{pmatrix} \mu_{xx} & \mu_{xy} & \mu_{xz} \\ \mu_{yx} & \mu_{yy} & \mu_{yz} \\ \mu_{zx} & \mu_{zy} & \mu_{zz} \end{pmatrix} \quad (5)$$

IV. Thermal problem

The considered heat source is the eddy current losses in the composite whose volume density can be determined by $P = \widehat{\boldsymbol{J}} \left([\rho^e]^{-1} . \boldsymbol{J} \right)$ where $\widehat{\boldsymbol{J}}$ is the complex conjugate of eddy-current density $\boldsymbol{J}$. The weak formulation of thermal problem reads:

$$\begin{aligned} &\int_{\Omega_c} W_n \rho C_p \tfrac{T_{j+1}}{\Delta t} d\Omega \\ &+ \int_{\Omega_c} \boldsymbol{\nabla} T_{j+1} [\lambda] \boldsymbol{\nabla} W_n d\Omega + \int_{\Gamma^c} W_n h T_{j+1} d\Gamma \\ &= \int_{\Omega_c} W_n P d\Omega + \int_{\Omega_c} W_n \rho C_p \tfrac{T_j}{\Delta t} d\Omega \end{aligned} \quad (6)$$

where T_j is the temperature rise at the instant j with respect to the initial temperature, the time step Δt is fixed. The parameters C_p, ρ and $[\lambda]$ are respectively the specific heat, the specific mass and the tensor of thermal conductivity of the material. The parameter h takes into account the natural convection and the radiation on the surface of the plate [10].

V. Simulation result

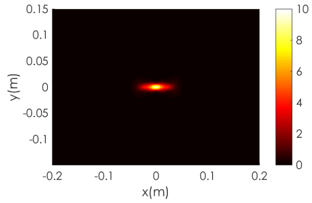
Fig. 2 shows the temperature of the material with various anisotropy ratio r_a which is defined as:

$$r_a = max(\rho_{xx,xy,...}^e)/min(\rho_{xx,xy,...}^e) \quad (7)$$

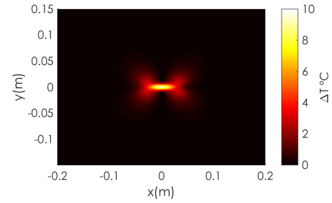
It is clearly shown that the thermal image patterns are strongly related to the ratio of anisotropy. In the case of strongly anisotropic material as CFRP, simulation results give a good accordance with measurement as shown in Fig. 3.

VI. Conclusion

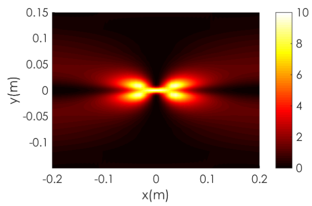
In the full paper, the method for identifying the electrical conductivity tensor using both the developed numerical model and experimental induction thermography data will be detailed.



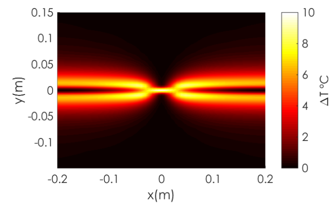
(a) $r_a = 1$ (isotropic material).



(b) $r_a = 10$.



(c) $r_a = 100$.



(d) $r_a = 1000$.

Fig. 2. Thermal image obtained at the end of heating phase.

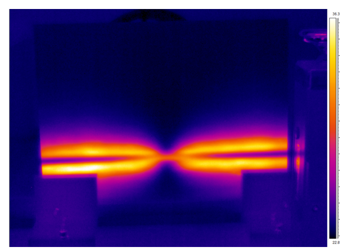


Fig. 3. Measured thermal image pattern obtained on a unidirectional CFRP.

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