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Effects of Coupled Fields on the Mechanical Response of Electrically Conductive Composites

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Abstract

In this work, the possibility for improvement of impact resistance of electric-current-carrying composite structures in the presence of an electromagnetic field is investigated. Governing equations describing the electro-magneto-mechanical interactions in anisotropic materials and the corresponding two-dimensional approximation for transversely isotropic plates are discussed. An efficient numerical procedure is developed to solve the resulting nonlinear boundary value problem for a long transversely isotropic current-carrying plate subjected to impact and pulsed electromagnetic loads. The numerical results show that the dynamic response of the plate highly depends on the magnitude and direction of the electromagnetic loads.

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Keywords: electro-magneto-mechanical coupling; electrically conductive composite; anisotropic plate, electromagnetic field, impact

Nomenclature

E	electric field vector
D	electric displacement vector
B	magnetic induction vector
H	magnetic field vector
ρ_e	charge density
j	electric current density vector
τ_{ij}	components of the mechanical stress tenor
F_i	components of the body force per unit mass
F_i^L	components of the Lorentz force per unit mass
u_i	displacement components
ρ	material density of solid body

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x_j	coordinates
t	time
$\boldsymbol{\sigma}$	electrical conductivity tensor
$\boldsymbol{\varepsilon}$	electrical permittivity tensor
ε_0	vacuum permittivity
$\mathbf{J}$	density of the external electric field
$\mathbf{1}$	unit tensor of second order
∇	gradient operator

1. Governing equations and solution procedure

Electromagnetic solids encompass a broad class of materials in which the interaction between mechanical and electromagnetic loads has a pronounced effect on the deformed state. The main focus of this work is on the effects of an electromagnetic field on the dynamic mechanical response of electrically conductive anisotropic composites. In particular, we are interested in carbon fiber polymer matrix composites that play a pivotal role in a number of industries, including aerospace and automotive. The present work aims to study the effects of pulsed electromagnetic fields on the impact response of carbon fiber polymer matrix composites.

In solids with electromagnetic effects, the interaction between mechanical and electromagnetic fields is due to the Lorentz ponderomotive force that is exerted by the electromagnetic field. Analysis of this field interaction requires simultaneous solving of Maxwell's equations for electromagnetic field

$$\begin{aligned} \operatorname{div}\mathbf{D} &= \rho_e, \quad \operatorname{curl}\mathbf{E} = -\partial\mathbf{B}/\partial t, \\ \operatorname{div}\mathbf{B} &= 0, \quad \operatorname{curl}\mathbf{H} = \mathbf{j} + \partial\mathbf{D}/\partial t, \end{aligned} \tag{1}$$

and equations of motion of continuous media

$$\frac{\partial \tau_{ij}}{\partial x_j} + \rho\left(F_i + F_i^L\right) = \rho \frac{\partial^2 u_i}{\partial t^2}. \tag{2}$$

It has been shown in the literature [1] that in the case of an electrically anisotropic and linear but magnetically isotropic solid body (which is the case of carbon fiber reinforced polymer matrix composites), the Lorentz ponderomotive force, $\mathbf{F}^L$, can be written in the form

$$\mathbf{F}^L = \rho_e\left(\mathbf{E} + \frac{\partial \mathbf{u}}{\partial t}\times\mathbf{B}\right) + \left(\boldsymbol{\sigma}\cdot\left(\mathbf{E} + \frac{\partial \mathbf{u}}{\partial t}\times\mathbf{B}\right)\right)\times\mathbf{B} + \left(\left((\boldsymbol{\varepsilon} - \varepsilon_0\cdot\mathbf{1})\cdot\mathbf{E}\right)\times\mathbf{B}\right)_\alpha \nabla\left(\frac{\partial \mathbf{u}}{\partial t}\right)_\alpha + (\mathbf{J}\times\mathbf{B}), \tag{3}$$

where Einstein's summation convention is adopted with respect to the index α. Therefore, the Lorentz force, which enters the equations of motion as a body force, makes the system of governing equations (1) and (2) coupled and nonlinear.

In the case of thin plates, three-dimensional (3D) Maxwell's equations (1) and equations of motion (2) may be reduced to 2D equations by means of the classic Kirchhoff hypothesis of nondeformable normals and the corresponding electromagnetic hypotheses introduced in [1,2]. In the hypothesis proposed in [2] it is assumed that the tangential components of the electric field vector and the normal component of the magnetic field vector do not change across the thickness of the plate. A 2D (quasi-static) approximation to Maxwell's equations is derived by representing electromagnetic field functions via series expansions with respect to the thickness coordinate and integrating 3D Maxwell's equations across the thickness of the plate [1]. The resulting 2D system of equations of motion and Maxwell's equations is a nonlinear mixed system of parabolic and hyperbolic partial differential equations of the form