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Modeling and simulation of electrification delivery in functionalized textiles in electromagnetic fields

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ABSTRACT

This work investigates the deformation of electrified textiles in the presence of an externally supplied magnetic field ($\boldsymbol{B}^{ext}$). The electrification is delivered by running current ($\boldsymbol{J}$) through the fibers from an external power source. Of primary interest is to ascertain the resulting electromagnetic forces imposed on the fabric, and the subsequent deformation, due to the terms $\boldsymbol{J} \times \boldsymbol{B}^{ext}$ and $\mathcal{P}\boldsymbol{E}$, where $\mathcal{P}$ is the charge density, $\boldsymbol{E}$ is the electric field and the current given by $\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}^{ext})$, where σ is the fabric conductivity, and $\boldsymbol{v}$ is the fabric velocity. As the fabric deforms, the current changes direction and magnitude, due to the fact that it flows through the fabric. The charge density is dictated by Gauss' law, $\nabla \cdot \boldsymbol{D} = \mathcal{P}$, where $\boldsymbol{D} = \epsilon\boldsymbol{E}, \epsilon$ is the electrical permittivity and $\boldsymbol{D}$ is the electric field flux. In order to simulate such a system, one must solve a set of coupled equations governing the charge distribution, current flow and system dynamics. The deformation of the fabric, as well as the charge distribution and current flow, are dictated by solving the coupled system of differential equations for the motion of lumped masses, which are coupled through the fiber-segments under the action of electromagnetically-induced forces acting on a reduced order network model. In the work, reduced order models are developed for (a) Gauss' law ($\nabla \cdot \boldsymbol{D} = \mathcal{P}$), (b) the conservation of current/charge, $\nabla \cdot \boldsymbol{J} + \frac{\partial \mathcal{P}}{\partial t} = 0$, and (c) the system dynamics, $\nabla \cdot \boldsymbol{T} + \boldsymbol{f} = \rho \frac{d\boldsymbol{v}}{dt}$, where $\boldsymbol{T}$ is the Cauchy stress and $\boldsymbol{f}$ represents the induced body forces, which are proportional to $\mathcal{P}\boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B}^{ext}$. A temporally-adaptive, recursive, staggering scheme is developed to solve this strongly coupled system of equations. We also consider the effects of progressive fiber damage/rupture during the deformation process, which leads to changes (reduction) in the electrical conductivity and permittivity throughout the network. Numerical examples are given, as well as extensions to thermal effects, which are induced by the current-induced Joule-heating.

1. Introduction

This work studies the deformation of electromagnetically-sensitive fabric (Figs. 1 and 2), induced by external mechanical, electric and magnetic fields. There are many applications for such materials, for example electromagnetic actuators, microelectromechanical systems (MEMS) and recently proposed electromagnetic ballistic fabric shields [58,61], whereby the Lorentz force is harnessed to enhance material resistance capabilities beyond purely mechanical effects, to help impede a high-velocity incoming projectile. In this analysis, we assume that the fabric can carry a charge. One way of achieving this is by adding, during fabrication, highly-conductive fine-scale particles to the usual polymer material that comprises most structural fabric. Alternatively, one can introduce conductive material via particle spray processing techniques. There are a variety of industrial particle deposition techniques, and we refer the reader to the surveys of the state of the art found in [28,29]. The "functionalization" or "tailoring" of materials by the addition of fine-scale material is a process that has a long history in engineering. The usual approach is to add particulates that possess a desired property to enhance a base (binder) material. There exist several methods to predict the resulting effective properties of materials with embedded particulates dating back to well over 100 years, for example to Maxwell [30,31] and Lord Rayleigh [40]. For a thorough analysis of many of such methods, see [44,23,21,33] for solid-mechanics oriented treatments and [15,16,56] for computational aspects. For a series of works on continuum modeling and finite-element simulation of the deformation of magnetoelastic functionalized membranes and films (for example mixtures of iron powder and polydimethylsiloxane), we refer the reader to recent studies by Barham et al. [4–8]. Applications for such materials are driven by the extensive sensor, actuator and MEMS industries. For specific applications, see [42,41,17,25,26,3,24,32].

The present study investigates the connection between the electromagnetic loading and fabric actuation, building on the recent analysis of Zohdi [58,61]. In those works, the charges were

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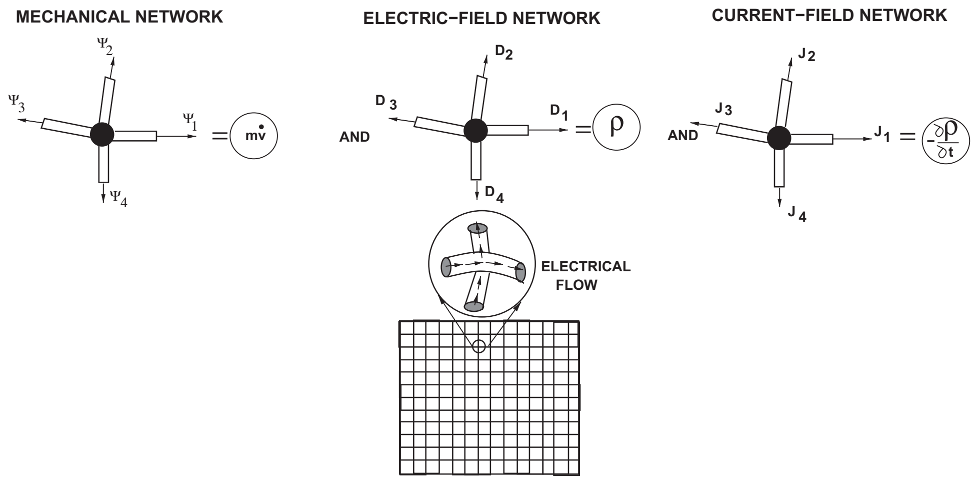

Fig. 1. A patch of fabric represented by network of woven-fabric by coupled fiber-segments. The fiber-segments are joined together by "pin-joint-like" connectors to form a network, whereby three sets of equations must be solved for the charge distribution, electric field and system dynamics.

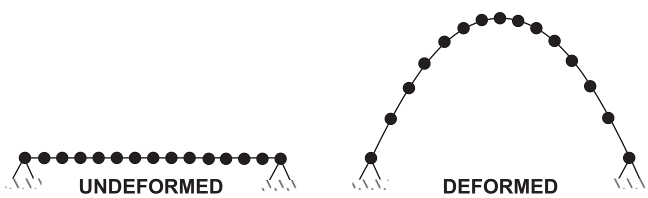

Fig. 2. A two-dimensional schematic of the deflection of the (lumped mass) fabric model, for a system that is clamped on both ends under (for example, unspecified, distributed) vertical loading. For details, on such models, see [47,54,58,48,52,38].

assumed to be electrostatic, i.e. intrinsically part of the fabric, in other words, the charges were considered to be *static within the fabric, i.e. not flowing*. For example, this type of "static" charge could be delivered in the form of an ion-implantation/bombardment/spray onto the fabric or, in some cases, one could consider materials that can be charged like a battery, provided that they have an inherent capacitance. However, in order to achieve much larger electric fields, a more robust, powerful and practical approach, is to run *live current* through the fabric system. This introduces a level of multifield complexity, both in terms of the modeling and simulation. *This is the focus of the analysis in this paper.*

The present work investigates the deformation of electrified textiles in the presence of an externally supplied magnetic field ($\boldsymbol{B}^{ext}$). The electrification is delivered by running current ($\boldsymbol{J}$) through the fibers from an external power source. Of primary interest is to ascertain the resulting electromagnetic forces imposed on the fabric, and the subsequent deformation, due to the terms $\boldsymbol{J}\times\boldsymbol{B}^{ext}$ and $\mathcal{P}\boldsymbol{E}$, where $\mathcal{P}$ is the charge density, $\boldsymbol{E}$ is the electric field and the current given by $\boldsymbol{J}=\sigma(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B}^{ext})$, where σ is the fabric conductivity, and $\boldsymbol{v}$ is the fabric velocity. As the fabric deforms, the current changes direction and magnitude, due to the fact that it flows through the fabric. The charge density is dictated by Gauss' law, $\nabla\cdot\boldsymbol{D}=\mathcal{P}$, where $\boldsymbol{D}=\epsilon\boldsymbol{E}, \epsilon$ is the electrical permittivity and $\boldsymbol{D}$ is the electric field flux. In order to simulate such a system, one must solve a set of coupled equations governing the charge distribution, current flow and system dynamics. The deformation of the fabric, as well as the charge distribution and current flow, are dictated by solving the coupled system of differential equations for the motion of lumped masses, which are coupled through the fiber-segments under the action of electromagnetically-induced forces acting on a reduced order network model.

Without any simplifications, such a system must be treated by direct continuum simulation of a fully coupled set of equations comprised of Maxwell's equations and the balance of momentum, which inevitably leads to non-trivial issues in numerical discretization and high-performance (large-scale) computing. Furthermore, depending on the type and level of actuation needed, the level of electromagnetism may induce thermal effects via Joule heating. A detailed account of full-blown continuum-based computational methods to simulate these effects can be found in [59] which employed the Finite Difference Time Domain Method (FDTD) and is beyond the scope of the current paper.[1] The development of reduced-order models that attempt to capture the essential features of such an electromagnetic delivery system, without resorting to full-scale, continuum, Maxwell-type, computations, is the subject of the present work. Specifically, reduced order models are developed for (a) Gauss' law ($\nabla\cdot\boldsymbol{D}=\mathcal{P}$), (b) the conservation of current/charge, $\nabla\cdot\boldsymbol{J}+\frac{\partial\mathcal{P}}{\partial t}=0$, and (c) the system dynamics, $\nabla\cdot\boldsymbol{T}+\boldsymbol{f}=\rho\frac{d\boldsymbol{v}}{dt}$, where $\boldsymbol{T}$ is the Cauchy stress and $\boldsymbol{f}$ represents the induced body forces, which are proportional to $\mathcal{P}\boldsymbol{E}+\boldsymbol{J}\times\boldsymbol{B}^{ext}$. A temporally-adaptive, recursive, staggering scheme is developed to solve this strongly coupled system of equations.

2. Fabric dynamics

The dynamics of the lumped charged-masses are given by

$$m_i\ddot{\boldsymbol{r}}_i=\underbrace{\boldsymbol{\Psi}_i^{tot}}_{\text{total}}=\underbrace{\boldsymbol{\Psi}_i^{em}}_{\text{electromagnetic forces}}+\underbrace{\sum_{I=1}^{4}\boldsymbol{\Psi}_{I_i}^{fiber}}_{\text{surrounding fiber}}, \tag{2.1}$$

where $i=1,2,\ldots,N$, where N is the number of lumped charged-masses, $\boldsymbol{\Psi}_i^{em}$ represents the electromagnetic contribution, $\boldsymbol{\Psi}_{I_i}^{fiber}$ represents the contributions of the four fibers intersecting at charged-mass i (Fig. 1) and m_i is the mass of a single lumped charged-mass (the total fabric mass divided by the total number of charged-masses). The forces from the Ith surrounding fiber-segment (there are four of them for the type of rectangular weaving pattern considered) acting on the ith lumped charged-mass is $\boldsymbol{\Psi}_{I_i}^{fiber}$. Clearly, $\boldsymbol{\Psi}_{I_i}^{fiber}$ is a function of the charged-mass positions ($\boldsymbol{r}_i$), which are all coupled together, leading to a system of equations. In order to solve the resulting coupled system, we develop an iterative solution scheme later in the presentation.

[1] The primary alternative to FDTD is the Finite Element Method for electromagnetics. In particular, see [13,14] for the state of the art in adaptive Finite Element Methods for electromagnetics.