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Multiphysics modeling of electromagnetically controlled shape memory polymer medical stents

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This paper deals with the multiphysics modelling of thermal-responsive shape memory polymer biomaterials. These materials can change their mechanical properties with the changing temperature. Thermal contactless control can be achieved by the adding electric or magnetic particles that can react to electromagnetic fields by generating heat. These materials can be used to design medical stents. During its deployment, the stent undergoes large mechanical deformations which make its modelling more involved. In this paper we present large deformations formulations of the multiphysics problem and use them to model the deployment of a shape memory polymer medical stent.

Index Terms—Biomedical implants, large deformation models, electromagnetic coupling, temperature control, thermomechanical processes.

I. INTRODUCTION

SHAPe MEMORY POLYMERS (SMP) biomaterials can be used for the prevention and cure of diseases such as the coronary heart disease and the stroke [1]. These smart materials can change their physical properties (morphing, Young modulus, etc.) when subjected to external stimuli such as temperature, pH and electromagnetic fields. They are mainly thermally activated and can be chosen biocompatible and biodegradable [1]. For applications inside the human body, thermal contactless control can be achieved by the addition of electric/magnetic (nano)particles inclusions that can react to electromagnetic fields. Fig. 1. depicts the deployment of a stent in the blood vessel.

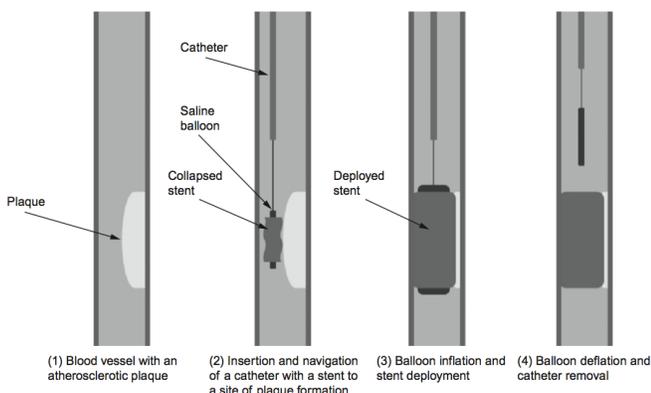


Fig. 1. Schematic of the deployment of a stent in a blood vessel [1].

Numerical models for composites biomaterials must account for the multiphysics coupling and the multiscale nature of the materials. This paper deals with the multiphysics modeling. The major challenge in developing multiphysics models in this application arises from the geometric non-linearity due to large mechanical deformations and that leads to the modification of the equations that govern the electromagnetic and thermal problems to account for motion. The other challenge is

handling material non-linearities due to the presence of plastic and viscous behaviour for mechanics and nonlinear behaviour for electromagnetism. This paper introduces a multiphysics quasistatic model using the Lagrangian formalism for an electromagnetically controlled vascular stent excited by a coil.

II. LAGRANGIAN MULTIPHYSICS FORMULATIONS OF THE COUPLED PROBLEM

The general coupled problem is derived from Maxwell's equations and conservation laws. Physical phenomena that take place on the deformed configuration can be described using the Eulerian coordinates \mathbf{x} . In this paper, we use the Lagrangian formalism and define the coupled problem using the coordinates \mathbf{X} defined on the undeformed configuration. The open domains Ω_0^{Mec} , Ω_0^{The} and Ω_0^{Ele} denote the undeformed computational domains for the mechanical, thermal and electromagnetic problems, respectively. The differential operators **Grad**, **Curl** and **Div** denote the gradient, rotational and divergence operators defined on the undeformed configurations. The Lagrangian description can be used when the mapping $\varphi : \Omega_0 \rightarrow \Omega_t$, $\mathbf{X} \mapsto \mathbf{x} = \varphi(\mathbf{X}) = \mathbf{X} + \mathbf{u}(\mathbf{X})$ is smooth enough. The domain Ω_t denotes the deformed configuration at the time $t \in [t_0, t_{\text{end}})$ and the vector field \mathbf{u} is the displacement field for large deformation.

The kinematics is described by the deformation gradient tensor and its determinant:

$$\mathbf{F} = \frac{\partial \mathbf{x}}{\partial \mathbf{X}} = \mathbf{1} + \mathbf{Grad} \mathbf{u} \quad , \quad J = \det \mathbf{F}. \quad (1)$$

In this paper, we consider a time-dependent thermal problem and quasistatic mechanical and electromagnetic problem thus neglecting electromagnetic waves and computing eddy currents by neglecting their contribution to the total field. The last assumption is reasonable for exciting sources with low frequencies and materials with low electric conductivity. The resulting problem can be solved using the $\mathbf{a}_s - \phi$ formulation where \mathbf{a}_s is the source vector potential, e.g., produced by a

coil and that can be pre-computed, and ϕ is the unknown scalar electric potential.

The Lagrangian description uses the pull-back of physical fields from the deformed to the undeformed configurations and the resolution of the multiphysics problem on the undeformed configuration. While the approach is very common for thermo-mechanical problems [2], [3], it needs to be extended to electromagnetic problems. The resolution of the electromagnetic problem is relatively easy for the electric scalar potential formulation which does not need to be defined in the air. In the context of the finite element method, it becomes involved when the resolution requires a mesh of the air. An interesting alternative consists in using integral methods [4], and restricting the accurate computation of eddy currents to the mechanical domain. In this paper we describe the coupled problem with the scalar electric formulation.

In the Lagrangian description, Maxwell's equations remain unchanged while Piola transformations depend on the differential-form [5]. The transformations of the Eulerian 0-differential form ϕ , 1-differential form \mathbf{e} , 2-differential form \mathbf{b} , 3-differential form \mathbf{f}_E and of the Eulerian second order tensors $\boldsymbol{\sigma}_E$ and $\boldsymbol{\kappa}_E$ read:

$$\begin{aligned} \Phi &= \phi, \quad \mathbf{A}_s = \mathbf{F}^T \mathbf{a}_s, \quad \mathbf{B}_s = J \mathbf{F}^{-1} \mathbf{b}_s, \quad \mathbf{f}_L = J \mathbf{f}_E, \\ \boldsymbol{\sigma}_L &= J \mathbf{F}^{-1} \boldsymbol{\sigma}_E \mathbf{F}^{-T}, \quad \boldsymbol{\kappa}_L = J \mathbf{F}^{-1} \boldsymbol{\kappa}_E \mathbf{F}^{-T}, \end{aligned} \quad (2)$$

where Φ , \mathbf{A}_s , \mathbf{B}_s , \mathbf{f}_L , $\boldsymbol{\sigma}_L$ and $\boldsymbol{\kappa}_L$ are Lagrangian electric scalar potential, source vector potential, source magnetic induction, volume force, electric and thermal conductivities expressed in the undeformed configuration. The indices E and L are used to denote Eulerian and Lagrangian quantities, respectively.

The weak form of the coupled problem reads [2], [6], [7] : find $\Phi \times \mathbf{u} \times \vartheta_L$ such that

$$\begin{aligned} & \int_{\Omega_0^{\text{Ele}}} \boldsymbol{\sigma}_L \mathbf{Grad} \Phi \cdot \mathbf{Grad} \Phi' \, d\Omega_0 + \int_{\Omega_0^{\text{Ele}}} \boldsymbol{\sigma}_L \partial_t \mathbf{A}_s \cdot \mathbf{Grad} \Phi' \, d\Omega_0 = 0, \\ & \int_{\Omega_0^{\text{Mec}}} \left(\mathbf{S}_{EP}(\mathbf{E}, \vartheta_L, \mathbf{Z}_L) : \delta \mathbf{E}' - \mathbf{f}_L \cdot \mathbf{u}' \right) \, d\Omega_0 = 0, \quad (2 \text{ a-b}) \\ & \int_{\Omega_0^{\text{The}}} \rho_0 c_p \frac{\partial \vartheta_L}{\partial t} \cdot \vartheta_L' \, d\Omega_0 + \int_{\Omega_0^{\text{The}}} \underbrace{\boldsymbol{\kappa}_L \mathbf{Grad} \vartheta_L}_{-\mathbf{q}_L} \cdot \mathbf{Grad} \vartheta_L' \, d\Omega_0 \\ & - \int_{\Omega_0^{\text{The}}} \underbrace{(\mathbf{F}(\boldsymbol{\sigma}_L \mathbf{E}_{\text{eff}} + \mathbf{J}_s)) \cdot (\mathbf{F}^{-T} \mathbf{E}_{\text{eff}})}_{w_L} \cdot \vartheta_L' \, d\Omega_0 \\ & + \int_{\Gamma_0^{\text{conv.,The}}} \underbrace{h_L(t)(\vartheta_L - \vartheta_{L,B})}_{\mathbf{n}_L \cdot \mathbf{q}_L} \cdot \vartheta_L' \, d\Gamma_0 = 0 \end{aligned} \quad (3)$$

holds for all test functions $\Phi' \times \mathbf{u}' \times \vartheta_L'$ in appropriate test function space.

In (2 a-b)–(3), \mathbf{S}_{EP} is the second Piola–Kirchhoff stress tensor which depends on the Green-Lagrange strain tensor $\mathbf{E} = \frac{1}{2}(\mathbf{F}^T \mathbf{F} - \mathbf{1})$ and a set of internal variables of the mechanical problem \mathbf{Z}_L . The quantity $\delta \mathbf{E}' = \mathbf{F}^T \mathbf{u}'$ and $\mathbf{E}_{\text{eff}} = -\partial_t \mathbf{A}_s - \mathbf{Grad} \Phi$ is the pull-back of the effective electric field $\mathbf{e}_{\text{eff}} = \mathbf{e} + \mathbf{v} \times \mathbf{b}$. The terms \mathbf{J}_s , w_L and h_L are the source electric current, the Joule losses and the convection coefficient. The last term of (3) accounts for the convection that results from the exchange of heat with a fluid at the temperature

$\vartheta_{L,B}$. The dependence of the electromagnetic force \mathbf{f}_L on the displacement \mathbf{u} is achieved through $J(\mathbf{u})$ and $\mathbf{F}(\mathbf{u})$ by:

$$\mathbf{f}_L = J^{-1} \mathbf{F} \underbrace{(\boldsymbol{\sigma}_L \mathbf{E}_{\text{eff}} + \mathbf{J}_s)}_J \times \mathbf{F} \underbrace{\mathbf{Curl}(\mathbf{A}_s)}_B. \quad (4)$$

III. NUMERICAL TESTS

The multiphysics problem has been solved for 3D problem with a cylindrical SMP stent described in [7]. Fig. 2. depicts the displacement \mathbf{u} , the Joule losses w_L and the temperature ϑ_L during the last process of recovery.

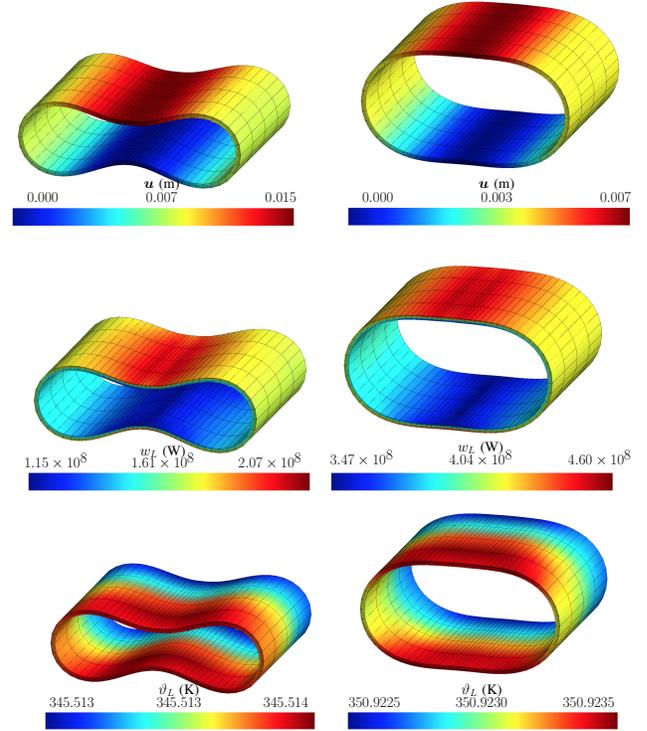


Fig. 2. Physical fields during the recovery. The left images correspond to $t = 4.78125 \times 10^{-3}$ s and the right images correspond to $t = 4.84375 \times 10^{-3}$ s. Top : displacement \mathbf{u} . Middle : Joule losses w_L . Bottom : Temperature ϑ_L .

In the extended paper, more theoretical details and results of the electro-thermo-mechanical problem will be given. We will also use the integral method to solve the electromagnetic problem.

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