THERMO-ELECTRICAL EQUIVALENTS FOR SIMULATING THE ELECTRO-MECHANICAL BEHAVIOUR OF BIOLOGICAL TISSUE

Cinelli, I.[1], Duffy, M[2], McHugh, P.E.[1]
[1]*Biomedical Engineering, NUI Galway, Ireland*
[2]*Electrical and Electronic Engineering, NUI Galway, Ireland*
i.cinelli1@nuigalway.ie
Keywords: Biomedical Engineering

Abstract

Thermo-electrical equivalents have been investigated to model different physical quantities defined by the same mathematical law structure. In this work the equivalents of the main laws and parameters are listed and classified in the static and dynamic domains. Abaqus software is used to validate the analogies in electrical, bio- and mechanical applications.

1. Introduction

Equivalence is one of most popular techniques to simulate the behavior of systems governed by the same type of differential equation.

In this case, a thermo-electrical equivalence is considered as a method for modelling the inter-dependence of electrical and mechanical phenomena in biological tissue. We seek to assess this approach for multi-scale models (from micro-structure to tissue scale) of biological media, such as nerve cells and cardiac tissue, in which the electrical charge distribution is modelled as a heat distribution in an equivalent thermal system.

This procedure allows for the reduction in problem complexity and it facilitates the coupling of electrical and mechanical phenomena in an efficient and practical way. Although the findings of this analysis are mainly addressed towards the electro-mechanics of tissue within the biomedical domain, the same approach could be used in other studies in which a coupled finite element analysis is required[1].

2. Method

In a first test case, a cell scale model of a nerve cell is chosen [1] in order to validate the charge distribution simulated electrically in [2] through heat transfer analysis. The steady state and time varying electrical behavior are analyzed based on the quasi-static theory assumptions for diffusion of charges in biological media [2].

The Cable Equation for the electrical transmission appropriately describes this behavior. This equation has the same mathematical structure as the Heat Equation, hence the overall distribution of charges across the nerve's membrane is equivalent to heat flux, and the voltage distribution is equivalent to temperature. Due to its time dependent behavior, the flow of charges is usually observed as an action potential.

To address the problem using the Abaqus CAE software, an isotropic axisymmetric 3-layer cylindrical model is generated, representing a section of a nerve cell (Figure 1). Particular focus needs to be paid to the representation of the membrane. Its non-linear properties are described by differential equations describing the voltage-dependent ionic currents of sodium, potassium and residual ions [3]. The Hodgkin-Huxley kinetic model is the most common and simple active ionic model, based on Kirchhoff's law [2]. Using this approach the membrane is represented as an electrical circuit composed of non-linear resistances in parallel with a capacitor and a current generator.

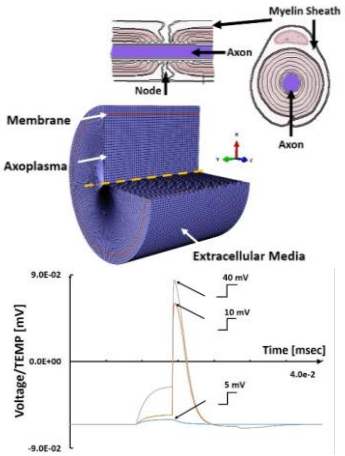

Figure 1: Axisymmetric 3-layer nerve cell model and the calculated action potential for 3 different step-input voltages.

3. Conclusion

As shown in Figure 1, the changes in membrane action potential are due to static and dynamic equilibrium, achieved by the balance of the ionic currents, implemented through the Continuity Equation and applied locally to the membrane domain. The transfer of ions across the nerve membrane is simulated using user-defined subroutines, particularly the USDFLD and DISP in FORTRAN. Hence, through the use of thermo-electrical equivalents, the propagation of the action potential can be simulated at the tissue scale and its trend compares favorably with published results, generated using an electrical simulation model of the nerve cell behavior [2].

8. References

[1]B.-J. Wang, Abaqus User' Conf., 1995.
[2]S. Elia, P. Lamberti,COMSOL Conference 2009, pp. 1–7.
[3]A. L. Hodgkin and A. F. Huxley, J. Physiol., vol. 117, pp. 500–544, 1952.