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Reduced Order Modelling of Neuron-Electrode Interfaces

INTRODUCTION

Implantable neural interfaces provide the opportunity to record neural activity, thereby allowing neuroscientists to study brain activity [1]. They can also be used to stimulate certain regions of the brain, or example in medical treatment of Parkinson or other diseases. This treatment is known as Deep Brain Stimulation. However, the function of the human brain and its interaction with such interfaces is highly complex and still not fully understood. Numerical models are an efficient way to study these interactions. The high complexity of such models leads to long computation times. Model Order Reduction (MOR) is a method for reducing their complexity, thereby reducing computation times and memory requirements.

Nonlinear Model in Ansys

The model of a cultured neuron placed on a planar substrate electrode proposed in [2] was adopted here and built in ANSYS. The voltage degrees of freedom of the neurons surface segments have been coupled. The Hodgkin-Huxley model [3] has been implemented in five positions using lumped elements. Between each loadstep during the solution process, the resistance parameters for Na and K are updated according to the current transmembrane voltage.

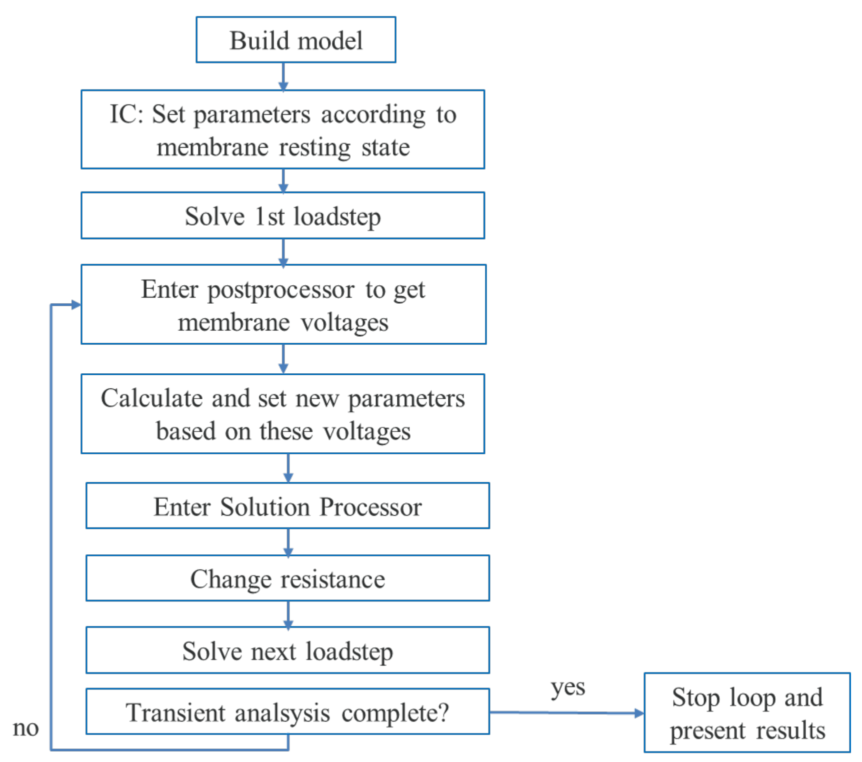

Fig. 1. The nonlinear Hodgkin-Huxley model is implemented using the singleframe restart method [4]. After each loadstep, the membrane voltages are retrieved from the postprocessor. The new resistance values for Na and K are calculated and set before the next loadstep is solved.

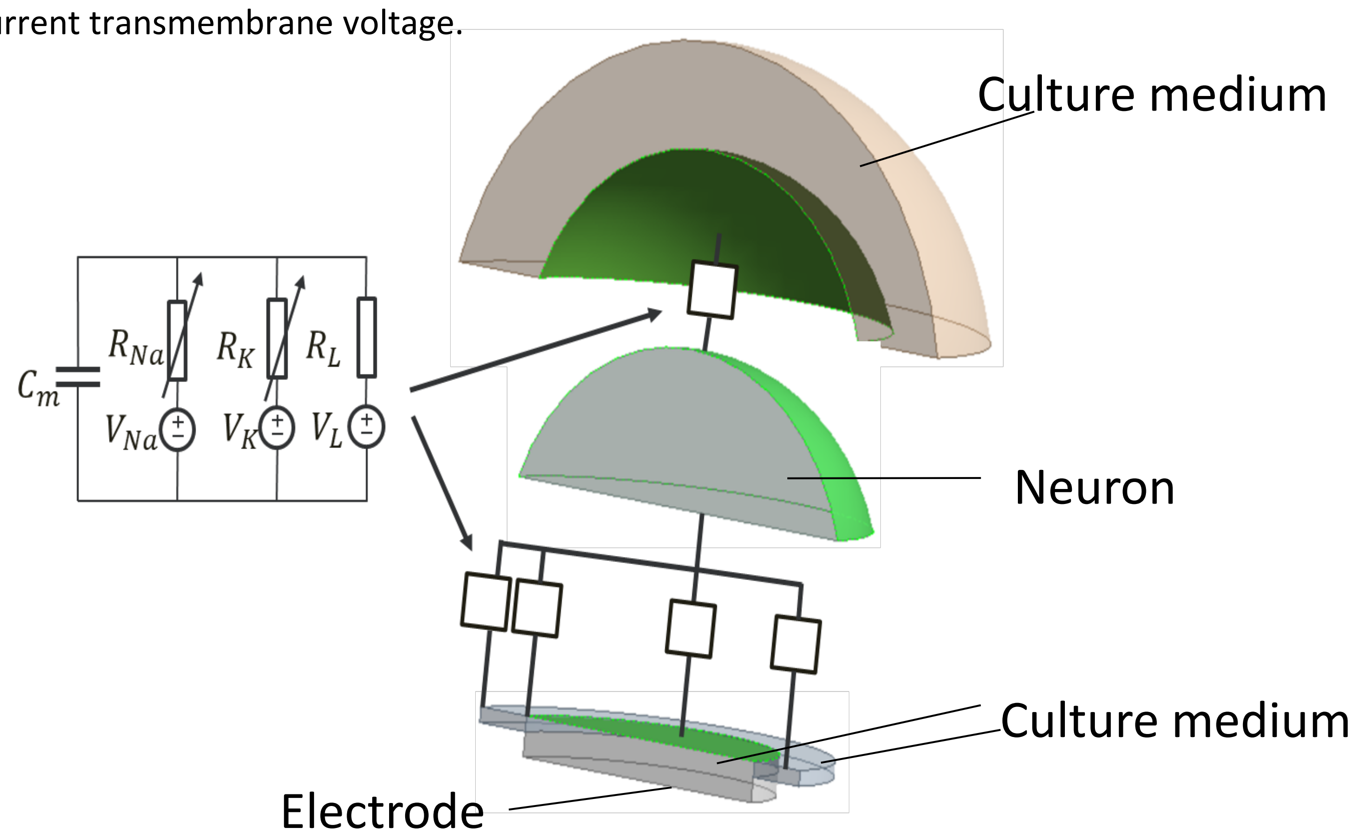

Fig. 2. The model of a cultured neuron placed on a planar substrate electrode proposed in [2] was adopted here and built in ANSYS. The voltage degrees of freedom of the neurons surface segments have been coupled. The sealing gap is divided into three rings, with each ring being coupled in the voltage domain. In total five Hodgkin-Huxley models are used to model the electrical properties of the neuron's membrane.

LINEAR MODEL AND MODEL ORDER REDUCTION

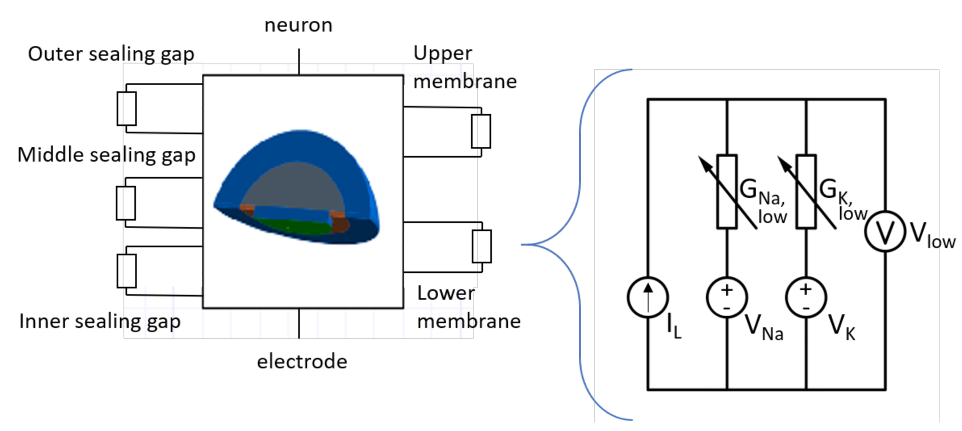

Fig. 3. Here, the nonlinear elements and the voltage sources of the five Hodgkin-Huxley models have been removed from the Ansys finite element model. The finite element model contains only the Leakage resistance R_L and the membrane capacitance C_m. This linear model is then reduced using the Krylov subspace method [5]. The remaining parts of the Hodgkin-Huxley model are connected to the reduced order model at system level.

After spacial discretization, the linear model can be represented as a set of ordinary differential equations [3]:

$$\Sigma_n \begin{cases} C\dot{x}(t) + Gx(t) = Bu(t) \\ y(t) = E^T x(t) \end{cases} \quad (1)$$

with state vector $x(t) \in R^n$, input vector $u(t) \in R^n$, output vector $y(t) \in R^p$, permittivity matrix $C \in R^{n \times n}$, electrical conductivity matrix $G \in R^{n \times n}$, input distribution matrix $B \in R^{n \times m}$, and output matrix $E \in R^{p \times n}$.

Krylov subspace based MOR [5] approximates Eq. (2) by a system of the same form, but with much smaller order, by projecting (1) onto the right Krylov subspace [5]. The orthonormal basis of the Krylov subspace was created by the Block Arnoldi algorithm [6].

SIMULATION RESULTS

A transient analysis is carried out for 90 ms. The electrode stimulates the system between 40 and 60 ms simulation time with a -5 nA pulse. The stepsize is 0.02 ms. Computations were carried out on a Dual Intel Xeon (Skylake, IBRS) processor, 2.99 GHz with six cores each.

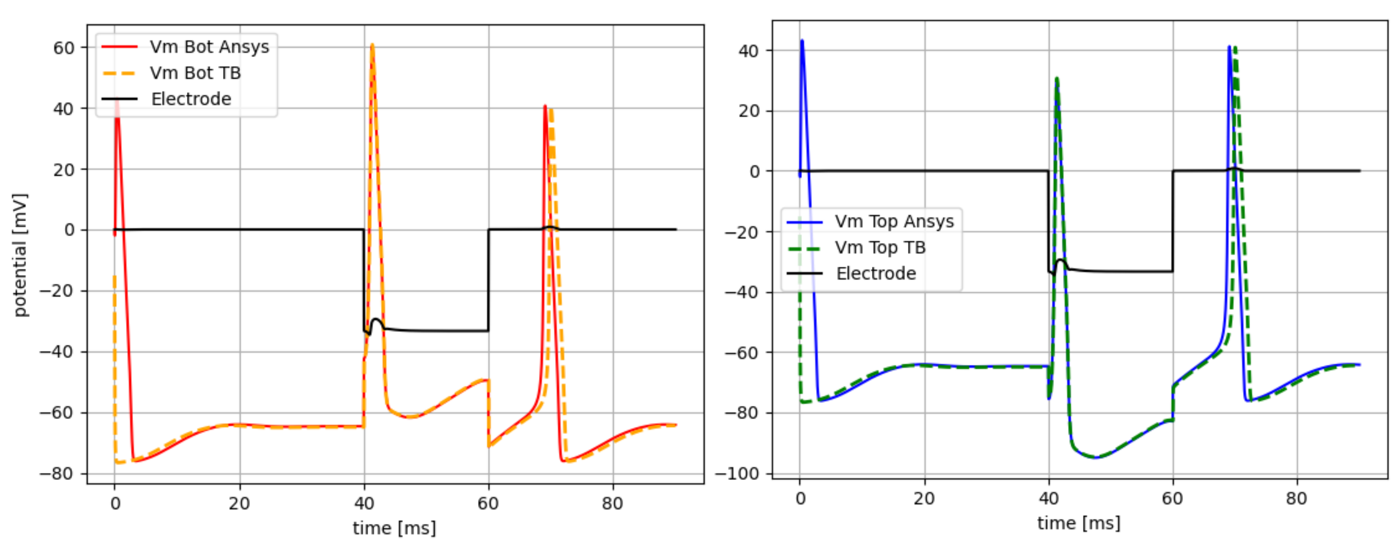

Table 1. CPU time comparison between the full order model and the reduced order model

	Full Order Model	System Level Model
Number of DOFs	8260	30
Computational Time	119 min	18 s

In the beginning, a stabilization process is necessary until the resting condition of the neuron is achieved. This is due to an initial condition of 0 V in the whole mode. The stimulating pulse triggers the neuron into generating an action potential. It takes 119 minutes to compute the full order model, consisting of 8260 degrees of freedom, The implementation using individual loadsteps leads to long computational times. However, this time can be reduced. The linear reduced model does not need single loadsteps. Further, the number of DOFs was reduced to 30.

CONCLUSIONS AND LITERATURE

- Computation times can be significantly reduced with the reduced order model.
- The long computation time of the full order model is partly caused by the implementation of the Hodgin-Huxley model using single loadsteps. A different implementation might reduce computation times of the full order model
- In the future, we will reduce the nonlinear model using appropriate methods

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