ECE:366 Course Project
Designing a Peripheral Neural Stimulation System

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***Abstract*—This project aims to design a neural stimulation system for the sciatic nerve stimulation. The aim is to use computational modeling to design a magnetic stimulation system for the sciatic nerve. In this work, we computed various aspects of neural circuit design, which includes defining simulation setup to generate extracellular potential, which consists of a simulator circuit and a magnetic coil. Further, at work, we realize this setup as an RLC circuit and find the currents through the coil and induced electric fields in space due to the current in the coil. We have evaluated the Electric field in space for different positions of the coil to optimize the coil position. We successfully found the most optimal position of the coil where the simulation threshold is minimal. Further, we proposed a novel design for the simulation setup to reduce the energy loss and stimulate the nerve with this design.**

I. Introduction

Our main objective is to design a magnetic stimulation system for neural stimulation of the sciatic nerve. The sciatic nerve is the largest nerve from the lower back to the heel and foot[1]. In reality, this is a complex project involving several design constraints. However, we made some assumptions about completing this project in a limited time. We assume the simulator circuit consists of only a DC voltage source and a capacitor. We assume a nerve thickness of 0.6 mm. Instead of modeling all the nerve fibers, model only one nerve fiber at the center of the nerve. The nerve fiber is myelinated with 55 nodes of Ranvier. The outer and inner diameters of the nerve fiber are 16 and 10 μm, respectively. The distance between two consecutive nodes is 1.6 mm. We also assume that the simulation domain is homogeneous. There is only one type of biological tissue for the nerve and surrounding space. We are provided with a NEURON model of this nerve.

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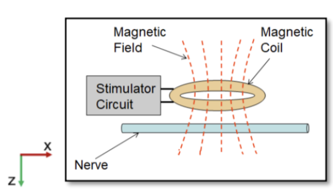

Fig. 1. Position of simulation setup and nerve in space.

Initially, we considered a single-turn circular coil with an inner diameter of 5 mm. The minimum separation (along the z-axis) between the nerve and the plane containing the coil is 0.5 mm. There is an offset of 4 mm along the y-axis between the centers of the nerve and coil. We assume that the coil comprises 22 AWG wires2]. The initial value of 400 V for the DC voltage source and capacitor is 5 mF.

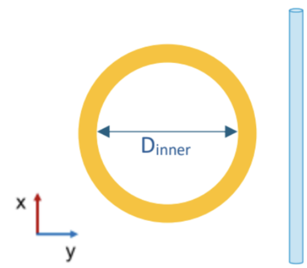

Fig. 2. Coil position in the XY Plane.

We perform some electric analysis to realize this setup as an RLC circuit and compute the current through the coil. In the next step, we calculate the electric field in the XY plane. Later in this work, we vary the position of the coil to find an optimized position, which will result in a minimum threshold. All these steps are discussed in the further subsections.

II. Methods and Results

The first step is realizing the simulation setup as an RLC circuit. Since we need an impulse current, we realize the setup as the circuit shown in Fig 3.

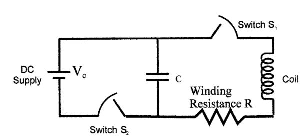

Fig. 3. Equivalent Circuit for the Simulation system.

The circuit[[3]] has a DC source Vc connected in parallel with a capacitor C. The coil can be represented as a series resistance R and inductor L. Resistance and Inductance of the coil are calculated based on 22 AWG wire properties. The 22 AWG wire has a Resistance per unit length equal to 0.0528363 Ω/m[4]]. The inner diameter of the coil is taken as 5 mm, and the diameter of the 22 AWG wire is 0.6438 mm. Inductance is calculated using an online Inductance calculator[5]]. Doing all these calculations in Python Script 1, we calculated all the needed parameters of the circuit.

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Net Resistance of circuit: 0.000829950659614332 ohm

Net Inductance of circuit: 6.69e-09 H

Net Capacitance of circuit: 0.005 F

DC Voltage source: 400 Volts
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Fig. 4. Circuit Parameters calculated using Python.

The circuit has two switches, S1 and S2. Initially, S1 is ON, and at time t = 0. The S1 is opened, and the S2 is closed simultaneously.

A. Current through coil

When switch S2 is closed, we can perform a transient circuit analysis. The second-order differential equation for the circuit can be written as

$$L\frac{d^2 i}{dt^2}+R\frac{di}{dt}+\frac{i}{C}=0 \tag{1}$$

$$\left.\frac{di}{dt}\right|_{t=0}=\frac{V_C}{L},\quad \left.i\right|_{t=0}=0 \tag{2}$$

Instead of solving this equation in the time domain, we take the Laplace Transform of the equation

$$I(s)=\frac{V_C}{Ls^2+Rs+\frac{1}{C}} \tag{3}$$

We further process this equation in Python Script 1 to find the Inverse Laplace Transform. This will provide us with the equation for the current in the coil.

$$i(t)=370466.3859e^{-62029.197t}\sin(161393.137t) \tag{4}$$

This equation is plotted for a time ranging from 0 to 5 msec.

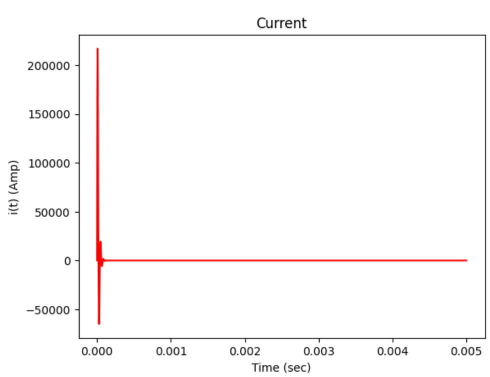

Fig. 5. Plot of current through the coil.

Further, we take the derivative of this equation to find the temporal change of the current in the nerve and plot it for a time ranging from 0 to 5 msec.

We normalized the derivative of the current with its maximum value to prove it in the NEURON model.

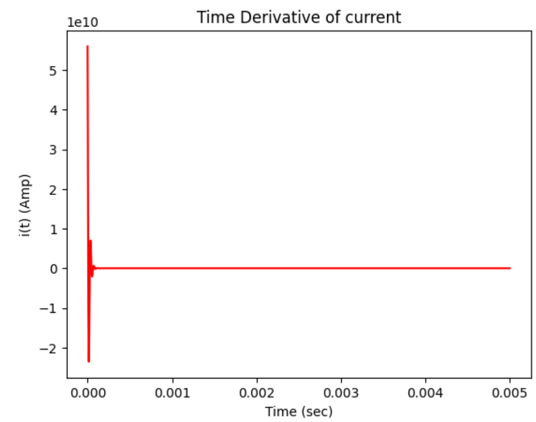

Fig. 6. Plot of the derivative of current through the coil.

B. Induced Electric Field in the XY Plane

To stimulate nerves, external stimuli are needed; we provide an electric field to the nerve. The induced Electric Field in the XY plane can be calculated using equation[6]

$$\mathbf{E}(\mathbf{r},t)=-\frac{\mu_0}{4\pi}\frac{\partial i}{\partial t}\int\frac{\mathbf{dl}}{|\mathbf{r}-\mathbf{r}'|} \tag{5}$$

where **i(t)** is the current flowing through the coil, **r** is the position where the field is calculated, **r'** is the position of a small segment of the coil, and **dl** is the vector oriented along the direction of the coil segment. Here we take the center of the coil at **(0 mm, 4 mm, 0.5 mm)** because of the offset condition as discussed earlier. We are taking positions only in the XY plane, i.e., in **r**, the component z = 0. Also, only the x component of the Electric field i.e. **Ex** will contribute to generating action potential in the nerve, so we are ignoring other components. Since we normalized the derivative of the current with its maximum value, we will only take the maximum value of the derivative of the current in the equation of the electric field. We processed this equation in Python Script 1 and generated a plot of **Ex** varying with x and y.

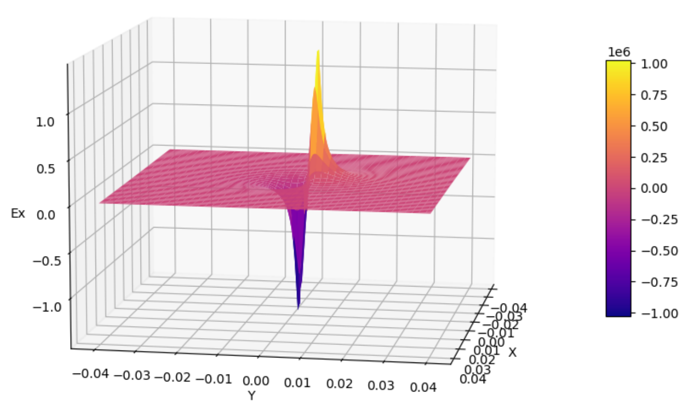

Fig. 7. Plot of the x component of the electric field induced by the coil.

The x and y vary from -40 mm to 40 mm in the space, with each having 200 samples between them. In the next step, we differentiate the **Ex** with respect to x to find the spatial distribution of the electric field along the X axis.

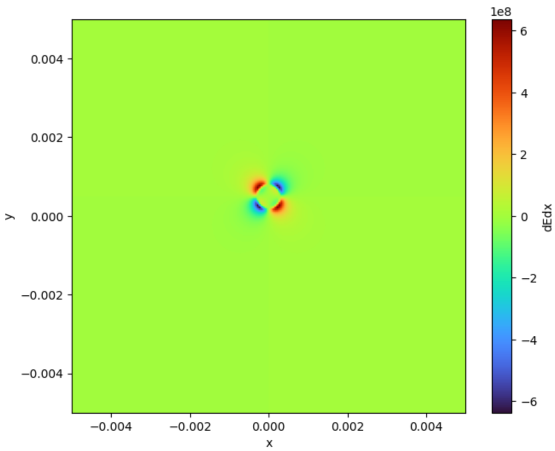

Fig. 8. Heat Map of **dEdx**.

C. Parametric Study

NEURON model of nerve takes a normalized **dEdx** only at the points at the nodes of Ranvier because other parts of the nerve are myelinated; thus, it is insulated from the electric field.

This study includes finding the nerve's simulation threshold at different coil positions. For the project's simplicity, we considered moving only along one axis at a time. Theoretically, the stimulation threshold is related to the scaling factor of the simulation. The scaling factor scales the DC voltage to the voltage the model needs to generate an action potential. In this section, we have found the scaling factor at different coil positions because our DC voltage is fixed, i.e., 400 Volts. Following plots are generated for varying the position of coil

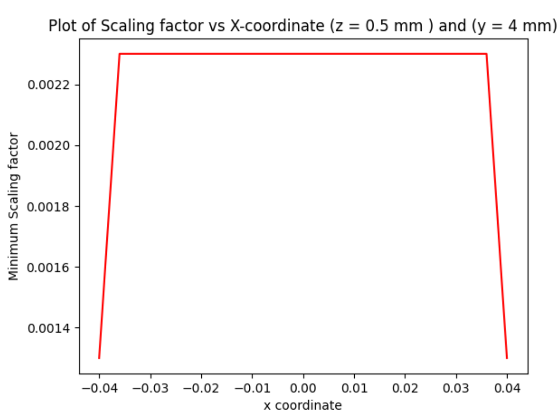

Fig. 9. Variation of Scaling factor along X axis

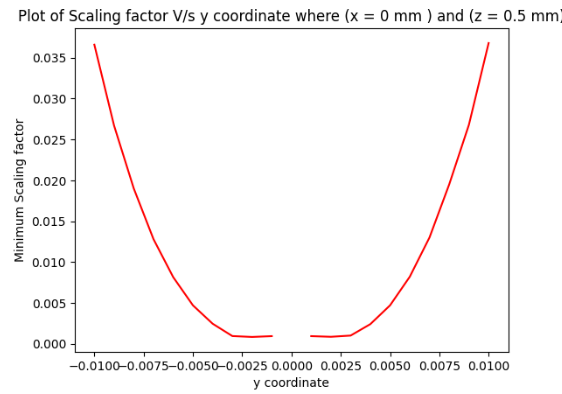

Fig. 10. Variation of Scaling factor along Y axis

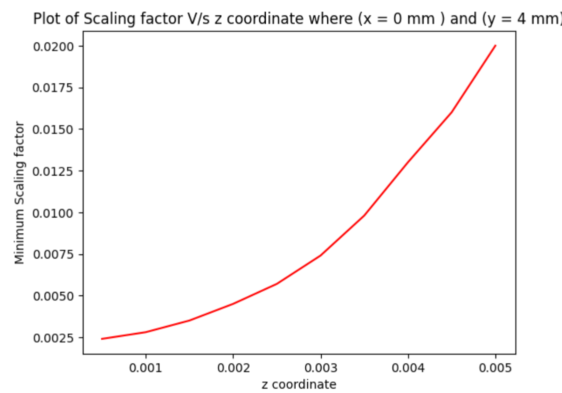

Fig. 11. Variation of Scaling factor along Z axis

The above plot shows the variation of the scaling factor along the X-axis, Y-axis, and Z-axis when the other two coordinates are at their initial position. When we move the coil along the X-axis, the scaling factor remains constant but decreases as we reach either end of the nerve.

The Y-axis movement of the coil shows an exponential change in the scaling factor. As we move away from the coil in either the positive Y-axis or a negative Y-axis, the scaling factor increases because the distance between the coil and the nerve increases. There is a discontinuity at y = 0 where no action potential is generated for any scaling factor. A similar trend is observed when the coil is moved away from a nerve in the Z-axis. The scaling factor increases exponentially.

III. Novel Design

A parametric study provided a position where the scaling factor can be minimal. This means that if we position our coil at that point, it needs the least DC supply to generate an action potential in the nerve. So we can design a simulation setup that works with that minimum DC supply. Initially, we are using the 22 AWG wire; we can use another type of wire in the novel design. Our sole target is to generate the minimum needed electric field and current at that position, generating action potential in the nerve. Due to time and experience constraints, we cannot design a novel simulation setup, but we have provided a theoretical explanation of how the novel design will look.

IV. Discussion and Conclusion

This project is a straightforward implementation of the real problem, as we have made some assumptions. We have calculated the possible results with this setup. This included the realization of the simulation system, generation of the electric field, modeling of the nerve, and parametric study to find the optimal position of the coil. A better NEURON model can be considered a bundle of nerves rather than a single nerve fiber. Doing this will give a more realistic model of nerve. However, this will make the NEURON model much more complex, making simulation too tricky. We can also improve the circuit, which will work on less input DC voltage, and different wire materials can be used. While doing the parametric study, we limit the motion of the coil to only one axis at a time. This is one of the significant limitations of this solution. However, in a real scenario, the coil can move at any point in 3D space. This will give the coil the most appropriate position with a minimal scaling factor. Here in the project, we have proposed a novel design of the simulation setup, which is at the most optimal position. However, this design is also being proposed while assuming all these assumptions.

V. Acknowledgement

We want to thank everyone for helping us with the project. We appreciate Dr. Pragya Kosta's support during the process. Her advice was essential for me to finish the work. Ankit Kumar Pal handles the computational portion, which includes converting the simulation configuration into a circuit and determining the coil's current and electric field. Sangam Rai carried out the parametric study as part of his work on the modeling portion of the project. We collaborated to develop a novel design for the simulation setup and did the report work together.

VI. References

All the references are added as a hyperlink at their respective position

Paper1 -Circuit Realisation of simulation setup]

Paper2 - K. Davey and C. M. Epstein, "Magnetic stimulation coil and circuit design," in IEEE Transactions on Biomedical Engineering

All online tools and references are provided directly.