NEID PROJECT

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***Abstract*—The aim of this project is to employ computational modeling approaches to build a neural stimulation model for the sciatic nerve, focusing on peripheral nerves The system consists of a magnetic stimulation coil, circuitry to deliver the stimulation current, and optimization of coil placement for effective stimulation The goal is to create a precise and non-invasive technique for activating the sciatic nerve, which is essential for lower limb motor and sensory abilities. Our analysis involves computing the current passing through the stimulation coil and its time derivative then computing the electric field induced in the proximal nerve and lastly, a parametric study to ensure controlled stimulation. With potential uses in neuromodulation.**

***Index Terms*—Electric field, Magnetic potential vector, Sciatic nerve, Time derivative, parameter Study, electric field gradient Electric field, Magnetic potential vector, Sciatic nerve, Time derivative, parameter Study, electric field gradient .**

I. Introduction

IN In medical technology, neuron simulation becomes essential tools that give us a non-invasive method for different neurological disorders. This project aims to create a neural stimulation system specifically for peripheral nerves, including the sciatic nerve. We aim to develop a magnetic stimulation model that can accurately activate the sciatic nerve. This involves three primary steps: Designing the simulation coil, the circuit to give the right simulation current through the coil, and optimizing the coil placement related to the simulation target site. To achieve the goal, we must consider a set of assumptions to simplify the process.

Assumptions

MODEL Design in fig1:

1) The simulator circuit consists of a DC voltage source and a capacitor ($C = 5$ mF).
2) The sciatic nerve has a thickness of 0.6 mm. We consider a single nerve fiber located at the center of the nerve, and it is myelinated with 55 nodes of Ranvier. The outer and inner diameters are 16 μm and 10 μm, respectively. The distance between two consecutive nodes is 1.6 mm.
3) Considering the homogeneous simulation domain means there is only one type of biological tissue for the nerve and surrounding space. Therefore, analytical equations are used to calculate the induced electric field.

Test Case

We consider a single-turn circular coil with an inner diameter of 5 mm. The minimum separation between the nerve and the plane containing the coil along the z-axis is 0.5 mm. The offset between the center of the nerve and the coil along the y-axis is 4 mm. Furthermore, the coil comprises 22 AWG wires and takes the initial value of 400 V for the DC voltage source.

II. Methods

A. Coil Current For Test Case

- Approach 1: for PART A

Solving the Circuit Differential Equation The differential equation for the RLC circuit (ignoring initial transient conditions and focusing on the response after closing the circuit at t=0 is:

$$V = L\frac{di}{dt} + iR$$

where R is :

$$R = \rho\frac{l}{A}$$

And L is the inductance calculated by the given formula.

- Approach 2: for Part A

To find the current $i(t)$ passing through the stimulator coil for the test case, first, we find the necessary parameters to compute $i(t)$, which include the permeability of free space (μ_0) given by $4\pi \times 10^{-7}$ H/m, initial voltage (V_0) of 400 V, and the capacitance (C) of 5 mF. Furthermore, we consider the inner diameter as 5 mm and the wire gauge as 22 AWG.

Next, we find the inductance (L) and resistance (R) of the coil. To find L, we use the formula:

$$L = N^2 \cdot \mu_0 \cdot \mu_r \cdot R\left(\ln\left(\frac{8R}{a}\right) - 2.0\right)$$

where N is the number of turns, R is the loop radius, a is the wire radius, and μ_r is the relative permeability.

To compute $i(t)$, we use the RLC equation. First, we calculate the discriminant using the formula:

$$D = \omega_1^2 - \frac{1}{LC}$$

where $\omega_1 = \frac{R}{2L}$ and $\omega_2 = \sqrt{\omega_1^2 - \frac{1}{LC}}$. If the discriminant is greater than zero, then it is overdamped, or if it's less than zero, it's underdamped. In our case, it's underdamped, formula for the overdamped and underdamped are given respectively:

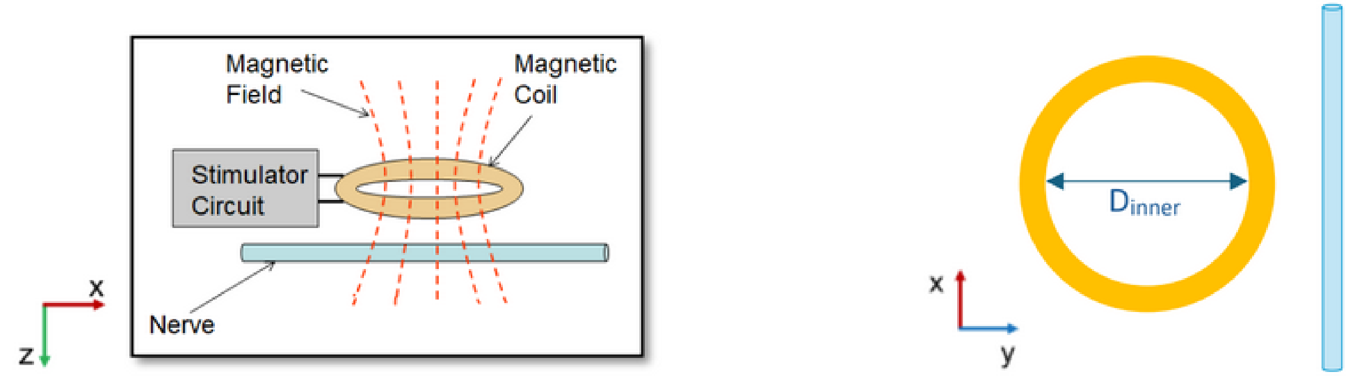

Fig. 1. Model Design

$$i(t) = V_0 C\omega_2 (e^{-\omega_1 t}) \left(\left(\frac{\omega_1}{\omega_2} \right)^2 - 1 \right) \sinh(\omega_2 t)$$

$$i(t) = V_0 C\omega_2 (e^{-\omega_1 t}) \left(\left(\frac{\omega_1}{\omega_2} \right)^2 + 1 \right) \sin(\omega_2 t)$$

Finally, we normalize the current derivative $\left(\frac{di}{dt}\right)$ for further use in the Parametric Study and finding the Electric field across nodes of ranvier.

B. 2D Electric Field For Test Case

Magnetic Field Calculation: For a circular coil centered at the origin, the magnetic field along the axis (z-axis in this case) can be approximated by:

$$B = \frac{\mu_0}{2} \frac{R^2 I}{(z^2 + R^2)^{3/2}}$$

The induced electric field equals the negative rate of change of the magnetic vector potential A

$$E = -\nabla\phi - \frac{\partial A}{\partial t}$$

or simply , To complete our model, we must calculate the electric field induced by a time-varying current in the coil. Maxwell's equations provide the relationship between the electric field and the coil current. The induced electric field E can be calculated from the coil current and its geometry by using the formula[3] :

$$\epsilon(r,t) = \left(\frac{dI(t)}{dt} \right) \left(-\frac{\mu_0 N}{4\pi} \int \frac{dl}{|r - r'|} \right)$$

C. Parametric Study

To find the optimal coil position concerning the nerve, we performed a parametric study to examine the variation of the simulation threshold concerning the coil position. Firstly, we established the range of coil positions concerning the nerve and considered the variation in the coil center's x, y, and z coordinates and coil orientation.

Next, we used a neuron simulation file, which provided us with two plots:

1) A time plot of V_m of the nerve fiber
2) A space plot of V_m of the nerve fiber

Simulating the propagation of action potentials along the nerve fiber to find the stimulation threshold.

Finally, we plotted how the stimulation threshold varies with the coil position.

III. Results

A. Plot of i(t) and Time Derivative $\frac{di}{dt}$

plots from fig2 to fig4

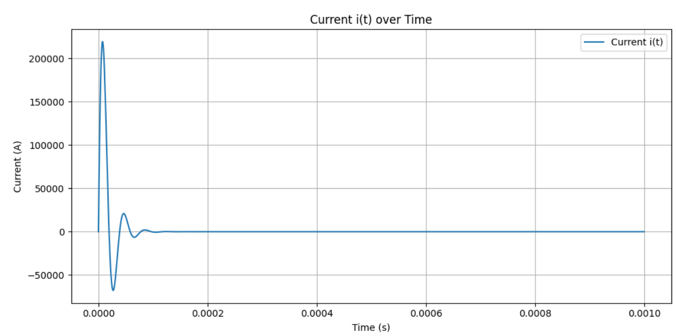

Fig. 2. current(i) in A vs time(t) in s

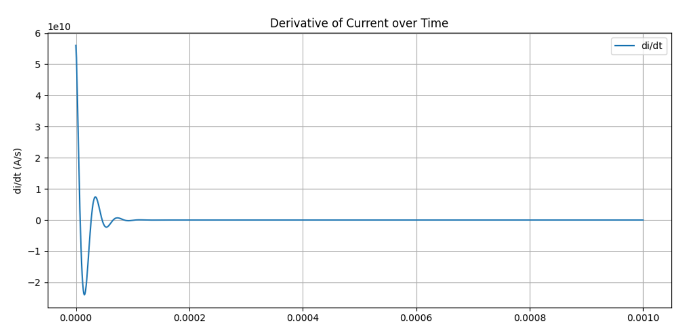

Fig. 3. current(di) A vs time(dt) in s

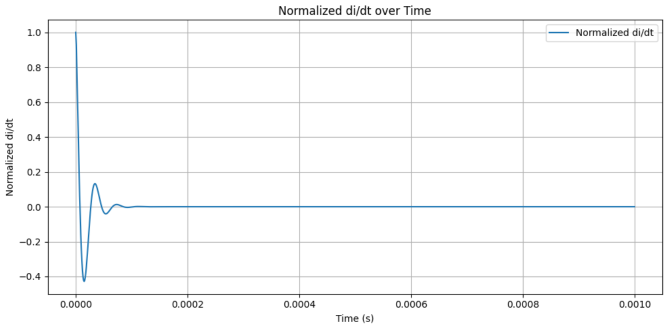

Fig. 4. Normalized current(dit) in A vs time(dt) in s

B. 2D Plots of The Electric Field Ex, Electric Field Gradient $\frac{dEx}{dx}$ and Heat-Map Plot of Electric Field Gradient $\frac{dEx}{dx}$

plots from fig5 to fig10

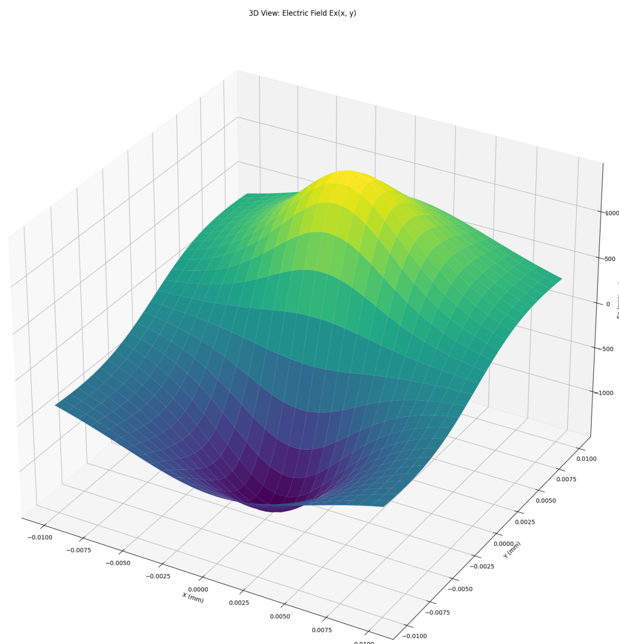

Fig. 5. Electric field in mV/mm

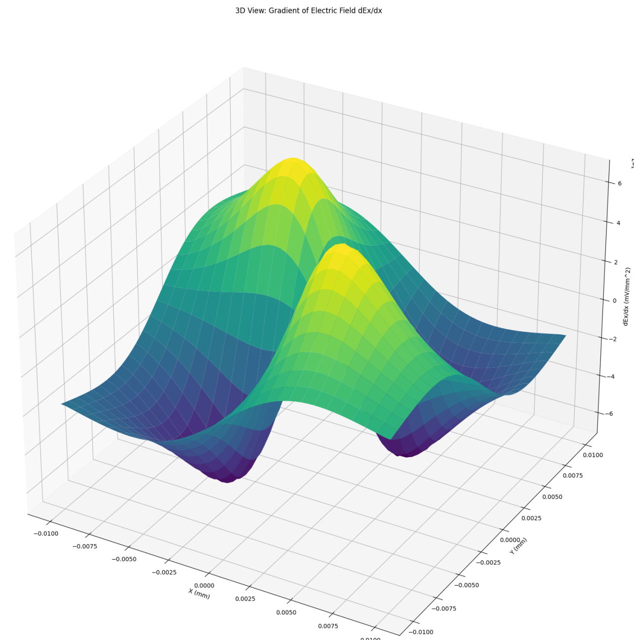

Fig. 6. Gradient of Electric field in mV / (mm^2)

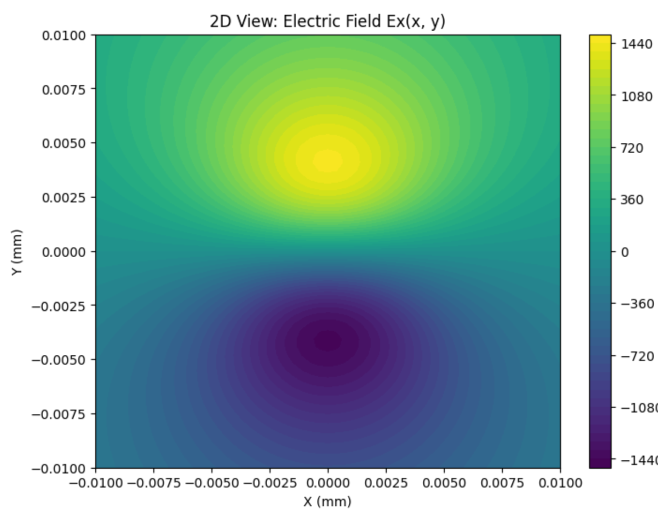

Fig. 7. 2D heatmap plot of Electric field in mV/mm

C. Parametric Study

D. Efficient Design For The Stimulation System.

To propose a more efficient design for the stimulation system, we focus on increasing the efficiency, enhancing spatial selectivity, and decreasing the power consumption of the existing system.

Firstly, we change the single-turn coil to a multi-turn coil design. A multi-turn coil generates a stronger magnetic field with lower current requirements, thereby improving the efficiency of the stimulation system. Additionally, we can optimize the coil geometry to match the orientation and shape of the nerve fiber. This will enhance spatial selectivity, providing stimulation to the target nerve rather than the surrounding tissues. Lastly, we can implement variable frequency stimulation by precisely controlling the stimulation parameters. This allows for better modulation of neural activity.

IV. Discussion

There is a complex interaction between the stimulation location and the coil's position and orientation concerning the nerve. Our model predicts that propagated action potentials measured at a common point far from the stimulating coil differ by a delay due to the change in the stimulation location if we use our coil to stimulate an action potential once and then reverse the polarity of the coil current and stimulate again.

This model may also be used to create stimulator/coil systems. The coil shape affects both the time course of the

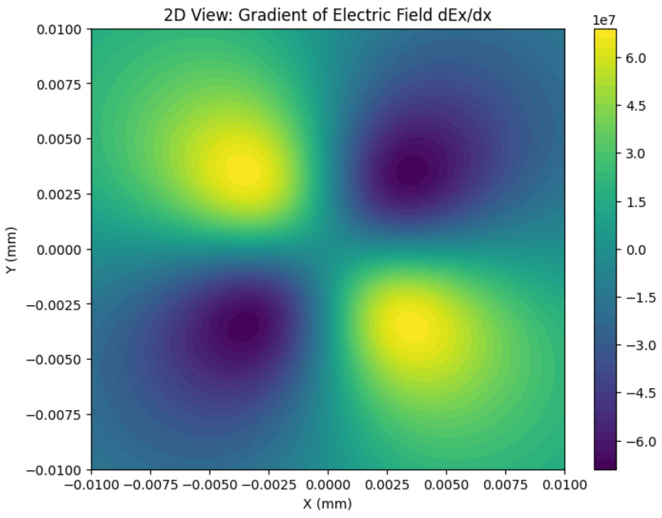

Fig. 8. 2D heatmap plot of Gradient of Electric field in mV/(mm^2)

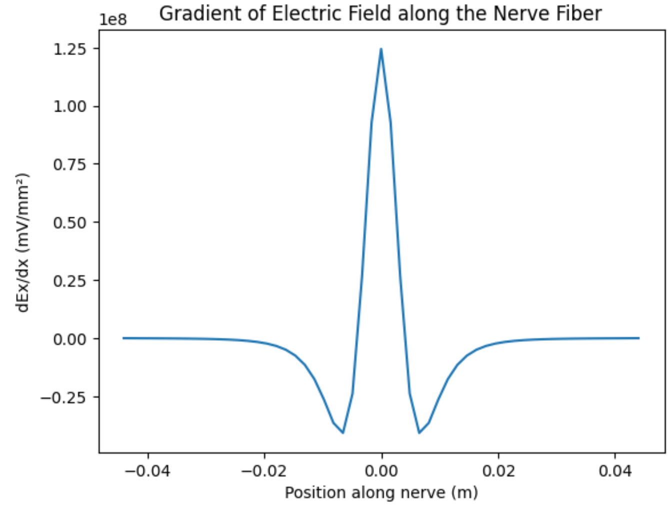

Fig. 10. simple 2D plot Gradient of Electric field in mV/(mm^2)

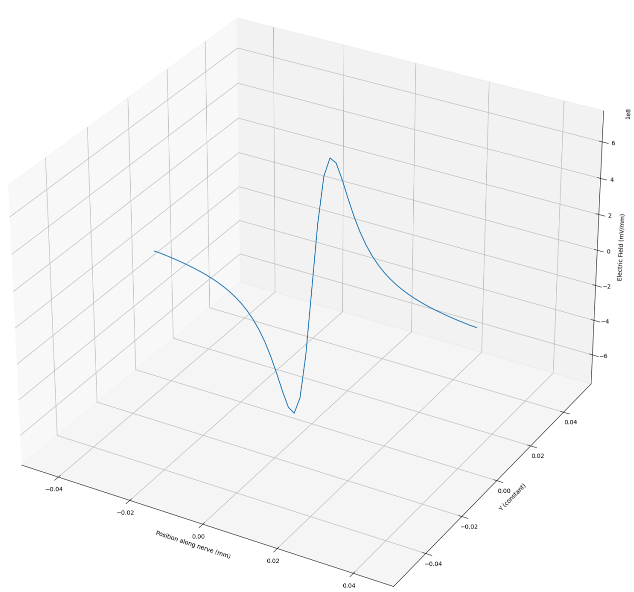

Fig. 9. simple 2D plot of Electric field in mV/mm

current pulse and the stimulus's spatial variation. The coil inductance determines how long the current pulse takes to complete. Modifications to the coil design that enhance the stimulus's spatial localization may also impact the current waveform's temporal properties.

V. Conclusion

In summary, this paper

We have computed a nerve fiber's reaction to electro-magnetic induction-induced electric fields. The current pulse shape, the spatial distribution of the produced electric field, and the interaction between the electric field and the nerve are the three aspects of electromagnetic stimulation that need to be considered simultaneously. Our main finding is that the axial derivative of the axial component of the produced electric field determines the stimulus's position and timing. coil translations in the perpendicular direction relative to the nerve to maximize stimulation threshold.

VI. Acknowledgment

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1) Mohammad Shariq 2020220 -
   - Collecting Research paper for Reference,
   - PART A of the Project
   - Part B of the project
   - Writing Report
   - Part C of the project
   - Part D editing more methods for novel design
1) Kunal Maurya 2020215 -
   - help in doing part B
   - Writing Report
   - Part C of the project
   - Part D

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stimulation;figure-of-eight coils;coil orientations;selectivity, URL:https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9261471&isnumber=9340019

4) B. J. Roth and P. J. Basser, ”A model of the stimulation of a nerve fiber by electromagnetic induction,” in IEEE Transactions on Biomedical Engineering, vol. 37, no. 6, pp. 588-597, June 1990, doi: 10.1109/10.55662. Abstract: A model is presented to explain the physics of nerve stimulations by electromagnetic induction. Maxwell's equations predict the induced electric field distribution that is produced when a capacitor is discharged through a stimulating coil. A nonlinear Hodgkin-Huxley cable model describes the response of the nerve fiber to this induced electric field. Once the coil's position, orientation, and shape are given and the resistance, capacitance, and initial voltage of the stimulating circuit are specified, this model predicts the resulting transmembrane potential of the fiber as a function of distance and time. It is shown that the nerve fiber is stimulated by the gradient of the component of the induced electric field that is parallel to the fiber, which hyperpolarizes or depolarizes the membrane and may stimulate an action potential. The model predicts complicated dynamics such as action potential annihilation and dispersion.¡¿ keywords: Electromagnetic modeling;Nerve fibers;Electromagnetic induction;Coils;Predictive models;Physics;Maxwell equations;Capacitors;Power cables;Shape,URL:https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=55662&isnumber=2011
5) https://www.researchgate.net/publication/21464859_Effects_of_coil_design_on_delivery_of_focal_magnetic_stimulation_Technical_considerations