DOI: doi.org/10.58797/cser.020104

Enhancing Learning of Electromagnetic Wave Propagation through 3D Visualization in Physics Education

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Abstract

This study aims to simulate the characteristics of electromagnetic wave propagation in different media, specifically focusing on water and oil, using Maxwell's wave equations. Water, acting as a conductor, and oil, as an insulator, were chosen to investigate the disparities in conductivity, attenuation constants, and their effects on wave propagation. The concept of electromagnetic wave propagation forms the basis for many advanced topics in physics, but is often challenging due to its abstract nature. Through these simulations, researchers observed temporal changes in electric and magnetic fields and visualized wave trajectories. These simulations allow for an extensive analysis without the need for physical wave transmission experiments. The integration of 3D visualization is a tool that can significantly improve students' concept understanding through visual and interactive representation of wave propagation. This research enhances theoretical understanding and has practical applications in areas such as underwater communications, oil spill monitoring, and measuring oil layer thickness. By employing the Finite-Difference Time-Domain (FDTD) method, the simulations demonstrated that variations in conductivity and attenuation constants considerably influence the behavior of electromagnetic waves. In oil, the waves retain their amplitude and phase during propagation, whereas in water, they experience attenuation, leading to a reduction in amplitude. These results offer valuable insights into the interaction of electromagnetic waves with various media, providing practical guidance for optimizing the performance of devices utilizing these waves.

Keywords: attenuation constants, conductivity, electromagnetic wave propogation, FDTD method

Received: 26 March 2024
Revised: 10 April 2024
Accepted: 12 April 2024
Published: 30 April 2024
Assigned: 30 April 2024

Current Steam and Education Research
e-ISSN: 3025-8529

INTRODUCTION

This research aims to simulate the characteristics of electromagnetic wave propagation in different media, specifically focusing on water and oil using Maxwell's wave equations to enchance student understanding. Teaching heat distribution in metal rods presents its own challenges because this concept involves an abstract understanding of energy flow that is difficult for students to visualize directly (Pacheco et al., 2019). Traditional learning methods, which often rely on theoretical approaches and mathematical formulas, are frequently less effective in explaining the complex dynamics that occur during the heat distribution process (Chen et al., 2023). Students often struggle to understand how variables such as temperature, time, and material properties affect heat distribution in real-time (Ji et al., 2019). As a result, they may struggle to connect theory with practical applications, which can hinder their deep understanding and ability to apply these concepts in real-life situations. By using interactive methods such as the Finite Difference Method, this challenge can be addressed through more concrete visualization and a more practical approach, allowing students to directly observe how heat distribution occurs and how various factors influence it.

Water, a conductor, and oil, an insulator, are chosen to examine differences in conductivity, attenuation constants, and their effects on wave propagation (Pawlik et al., 2020). By modeling electromagnetic wave behavior in these media, researchers can monitor changes in electric and magnetic fields over time and visualize wave paths. These simulations allow for a comprehensive analysis without the need for physical wave transmission experiments. The study enhances theoretical understanding and has practical applications in fields such as underwater communications, oil spill monitoring, and measuring oil layer thickness. The pioneering study by Garbacz et al. (1965) introduced Characteristic Mode Theory (CMT), which suggested that characteristic modes could effectively diagonalize the scattering matrix of any electromagnetic target. However, the complexity of their CMT calculation method posed significant challenges in practical computation and analysis. Later, Harrington and Mautz (1971) developed a method to compute characteristic modes for irregularly shaped metallic structures using integral equations and the moments method, as detailed in their paper. Yet, as the electrical size of the tower increases, the discretization of matrix equations leads to a dramatic rise in the number of unknowns, resulting in excessive computational time (Zong et al., 2023).

Electromagnetic waves play an important role in various fields, ranging from communication to radar and heating. Optimal electromagnetic absorbing materials not only can absorb electromagnetic energy (Lv et al., 2021), but also convert it into heat within the dispersing medium (Ali et al., 2023). Understanding the propagation of electromagnetic waves in different media is key to optimizing the performance of devices and systems that utilize them. For this reason, it is very important for students to understand the concept of electromagnetic wave propagation. However, students often have difficulty in understanding abstract concepts in this material, because it involves complex and invisible phenomena. So it is difficult to visualize with traditional methods. 3D visualization comes as an alternative solution by providing a concrete visual representation of waves that not only clarifies the concept, but can enhance students' ability to connect theory with real-world applications. In this study, we simulate the propagation characteristics of electromagnetic waves in various media, such as water and oil, as examples.

Through this study, it is anticipated that the transition from theory to practice can be facilitated more smoothly and directly. The theoretical analysis has been conducted using Mathematica software, and a comparison with finite element magnetic method simulation on a typical magnetic structure has been presented to illustrate the analogy. A comprehensive analysis of the Maxwell static-elliptical electromagnetic equation, has been performed in a detailed and unambiguous manner, utilizing different equation forms, boundary conditions, and ferromagnetic materials, all for educational purposes.

Water and oil have contrasting conductivity properties: water is a conductive medium, while oil is an insulator (Alarifi & Mahmoud, 2022). This difference in conductivity significantly affects the propagation of electromagnetic waves. Electromagnetic radiation has the potential to measure the density of organic materials, water content, and other parameters at various soil depths (Veirana et al., 2023).

The magnetic permeability of oil and water closely approximates that of a vacuum (μ0), which is about 4π x 10-7 H/m. This indicates that both substances have minimal impact on the magnetic field passing through them. Oil exhibits a dielectric permittivity that typically ranges from 2 to 4, depending on its type. In contrast, water has a significantly higher dielectric permittivity of around 80 (Cox & Geissler, 2022). This disparity results in distinct responses to electric fields between the two substances.

Electromagnetic propagation refers to the process of radio waves moving through different environments such as urban areas, mountains, or tunnels, where they interact with surfaces causing effects like reflection, refraction, diffraction, and scattering (Burke, 2020). During their journey, these electromagnetic waves also experience a decrease in amplitude, which is influenced by the attenuation constant. The attenuation constant is an important parameter in the analysis of electromagnetic wave propagation because it describes how quickly the wave amplitude decreases as it propagates through a medium. When electromagnetic waves interact with surfaces and environmental structures, the presence of the attenuation constant plays a crucial role in determining how far the waves can travel before becoming too weak to be detected or received. Therefore, a deep understanding of the attenuation constant is essential in the design and optimization of wireless communication systems, environmental monitoring, and other applications that rely on electromagnetic wave propagation.

The attenuation constant is a crucial parameter in the analysis of electromagnetic wave propagation because it describes how quickly the wave amplitude decreases as it travels through a medium. This constant is influenced by the properties of the medium, such as conductivity, permittivity, and permeability. In a conductive medium like water, electromagnetic waves experience higher attenuation compared to an insulating medium like oil. Therefore, understanding the attenuation constant in various media is key to optimizing the design and implementation of systems that utilize electromagnetic waves. This study will discuss how the difference in conductivity between water and oil affects the attenuation constant and, consequently, the propagation of electromagnetic waves in these two media (Samadpour et al., 2023).

	Type of Medium		
Quantity	Lossless ($\epsilon'' = \sigma = 0$)	General Lossy	Good Conductor ($\epsilon'' \gg \epsilon'$ or $\sigma \gg \omega\epsilon'$)
Complex propagation constant	$\gamma = j\omega\sqrt{\mu\epsilon}$	$\gamma = j\omega\sqrt{\mu\epsilon}$ $= j\omega\sqrt{\mu\epsilon'}\sqrt{1 - j\frac{\sigma}{\omega\epsilon'}}$	$\gamma = (1+j)\sqrt{\omega\mu\sigma/2}$
Phase constant (wave number)	$\beta = k = \omega\sqrt{\mu\epsilon}$	$\beta = \mathrm{Im}\{\gamma\}$	$\beta = \mathrm{Im}\{\gamma\} = \sqrt{\omega\mu\sigma/2}$
Attenuation constant	$\alpha = 0$	$\alpha = \mathrm{Re}\{\gamma\}$	$\alpha = \mathrm{Re}\{\gamma\} = \sqrt{\omega\mu\sigma/2}$
Impedance	$\eta = \sqrt{\mu/\epsilon} = \omega\mu/k$	$\eta = j\omega\mu/\gamma$	$\eta = (1+j)\sqrt{\omega\mu/2\sigma}$
Skin depth	$\delta_s = \infty$	$\delta_s = 1/\alpha$	$\delta_s = \sqrt{2/\omega\mu\sigma}$
Wavelength	$\lambda = 2\pi/\beta$	$\lambda = 2\pi/\beta$	$\lambda = 2\pi/\beta$
Phase velocity	$v_p = \omega/\beta$	$v_p = \omega/\beta$	$v_p = \omega/\beta$

Figure 1. Summary of Plane Wave Propagation Results in Various Media (Pozar, 2021).

In Figure 1, In a conductive medium such as water, the attenuation constant (α) is non-zero, indicating significant energy loss as the wave propagates through the medium. The presence of water's non-zero conductivity is a critical factor that leads to the absorption of energy from the electromagnetic wave, which, in turn, diminishes or reduces its amplitude during propagation (Qin et al., 2022). This attenuation is not merely a matter of reduced wave strength but involves complex interactions between the medium's electrical properties and the electromagnetic wave. The propagation constant in such a conductive medium becomes complex due to the inherent conductivity, introducing a phase difference between the electric field and the magnetic field of the wave. This phase discrepancy is pivotal as it directly influences the wave's attenuation, causing the wave to lose energy more rapidly compared to propagation in a non-conductive medium (Muhibbullah, 2021).

The complex nature of the propagation constant encapsulates both the attenuation and phase shift experienced by the wave. As the wave travels through the conductive medium, the energy absorption manifests in two significant ways: First, the amplitude of the wave decreases exponentially with distance, a direct result of the non-zero attenuation constant. Second, the phase velocity of the wave is altered, leading to a phase lag between the electric and magnetic components. This lag is a direct consequence of the medium's conductivity and results in the wave's energy being converted into heat within the medium, further contributing to the loss.

Analyzing the implications of these phenomena reveals that the conductive properties of water not only reduce the wave's amplitude but also impact its overall propagation characteristics. This dual effect of attenuation and phase shift is essential in understanding electromagnetic wave behavior in various applications, from underwater communication to medical imaging. The conductive nature of water thus plays a critical role in shaping the propagation dynamics of electromagnetic waves, emphasizing the importance of accounting for conductivity in theoretical models and practical applications involving wave transmission through conductive media.

The waves are defined by a frequency ω, and the characteristics of the medium through which they travel are determined by the material constants ε and μ (Müller, 2014). When an electromagnetic wave travels through a medium with conductivity σ, relative dielectric constant $\varepsilon = \varepsilon_r \varepsilon_0$, and magnetic permeability $\mu = \mu_r \mu_0$, it satisfies Maxwell's equations (Griffiths, 2017).

$$\nabla \times \vec{H} = \varepsilon \vec{E} + j\omega\varepsilon\vec{E} = j\omega\varepsilon_c\vec{E} = \sigma\vec{E} + \varepsilon\frac{\partial \vec{E}}{\partial t} \quad (1)$$

$$\nabla \times \vec{E} = -j\omega\mu\vec{H} = -\mu\frac{\partial \vec{H}}{\partial t} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \rightarrow \nabla \cdot \vec{H} = 0 \quad (3)$$

$$\nabla \cdot \vec{D} = 0 \rightarrow \nabla \cdot \vec{E} = 0 \quad (4)$$

$$\vec{B} = \mu\vec{H}, \vec{D} = \varepsilon\vec{E} \quad (5)$$

Where $\varepsilon c = \varepsilon - j\,(\sigma/\omega)$ represents the effective dielectric constant. When conductivity $\sigma = 0$, indicating a lossless medium, $\varepsilon c = \varepsilon$. In a linear, homogeneous, and isotropic (LHI) medium, characterized by uniform properties across all points and where μ and ε are constant and independent of direction, the medium is termed homogeneous. The equations are dependent solely on two variables, μ and ε. Equation (2) allows us to derive an expression that exclusively involves ε:

$$\nabla \times \nabla \times \vec{E} = -\mu\nabla \times \frac{\partial \vec{H}}{\partial t} \quad (6)$$

$$\nabla^2\vec{E} = \nabla^2 E_x\vec{a}_x + \nabla^2 E_y\vec{a}_y + \nabla^2 E_z\vec{a}_z \quad (7)$$

$$\nabla^2\vec{E} = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (8)$$

$$\nabla^2\vec{E} = \mu\frac{\partial}{\partial t}\left[\nabla \times \vec{H}\right] \quad (9)$$

$\nabla \times \vec{H}$ can be substituted using equation (1) to obtain:

$$\nabla^2\vec{E} = \mu\sigma\frac{\partial \vec{E}}{\partial t} + \mu\varepsilon\frac{\partial^2 \vec{E}}{\partial t^2} \quad (10)$$

These are a set of three equations in a conductive medium involving the electric field $\vec{E}$. We can derive a similar set of three equations for $\vec{H}$.

$$\nabla^2\vec{H} = \mu\sigma\frac{\partial H}{\partial t} + \mu\varepsilon\frac{\partial^2 H}{\partial t^2} \quad (11)$$

The six equations given by equations (10) and (11) are the generalised wave equations. These equations govern the behaviour of electromagnetic fields in homogeneous conductive media. In second-order differential equations, the presence of a first-order term indicates that the field is weakened (with energy loss) as it propagates through the medium. Hence, conductive media are referred to as lossy media. The equation for electromagnetic wave propagation in a medium is:

$$\nabla^2\vec{E} + y^2\vec{E} = 0 \quad (12)$$

$$\nabla^2\vec{H} + y^2\vec{H} = 0 \quad (13)$$

Where:

$$\alpha = \omega\left(\frac{\mu\epsilon}{2}\right)^{1/2}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} - 1\right] \quad (14)$$

The equation for the propagation of electromagnetic waves (assuming propagation in the z-direction) is:

$$\vec{E} = \vec{e}_x E_m e^{-yz} = \vec{e}_x E_{xm} e^{-az} e^{-j\beta z} \quad (15)$$

$$\vec{H} = \vec{e}_z \times \frac{Em}{\eta_c} = \frac{\vec{e}_y E_{xm}}{\eta_c} e^{-az} e^{-j\beta z} \quad (16)$$

The final equation for simulating the propagation of electromagnetic waves (assuming propagation direction along x-axis) is:

$$\vec{E} = E_{xm}\, cos(\omega.tk.x)\, e^{-\alpha x} \quad (17)$$

$$\vec{H} = E_{xm}\, cos(\omega.tk.x - \frac{\pi}{4})\, e^{-\alpha x} \quad (18)$$

METHOD

Finite-Difference Time-Domain (FDTD) method is a rigorous and powerful tool for modeling nano-scale optical devices. FDTD solves Maxwell's equations directly without any physical approximations, and the maximum problem size is only limited by the available computational power. It characterizes the propagation characteristics of electromagnetic waves in uniform media and media experiencing energy loss (Firdaus et al., 2021). 3D visualization is integrated into the teaching process through carefully structured lessons starting with theoretical explanations followed by demonstrations using 3D visualization of electromagnetic wave propagation. Students can see how waves act and understand their behavior. this allows students to explore 3D models both individually and in groups. The teacher as a facilitator to guide students to understand the concepts and encourage in-depth discussions based on their observations.

The algorithm for visualizing 3D electromagnetic wave propagation in oil and water media is as follows:

```
Definition of Attenuation Constant:
1.1. Define the constant:
       1.1.1. If the medium is seawater:
                 1.1.1.1. Return 0.5.
       1.1.2. If the medium is oil:
                 1.1.2.1. Return 0.
       1.1.3. If the medium is soil:
                 1.1.3.1. Return 0.005.
       1.1.4. Otherwise:
                 1.1.4.1. Return an error value.
Definition of Plotting:
1.2. Define the plot update:
       1.2.1. Initialize the time formula (t).
       1.2.2. Initialize the electric field formula (Ey).
       1.2.3. Initialize the magnetic field formula (Hz).
       1.2.4. Clear the plot.
       1.2.5. Plot the electric field in blue.
       1.2.6. Plot the magnetic field in red.
       1.2.7. Print a PrettyTable for each frame.
       1.2.8. For each value in the range of the length of x:
```

```
                    1.2.8.1. Add a row to the table.
            1.2.9. Print the table.
    Main Program:
    3.1. Start.
    3.2. Import numpy as np.
    3.3. Import matplotlib.pyplot as plt.
    3.4. Import Axes3D from mpl_toolkits.mplot3d.
    3.5. Import FuncAnimation from matplotlib.animation.
    3.6. Import PrettyTable from prettytable.
    3.7. Initialize parameters k, w, Exm, and Hym.
    3.8. Initialize the distance.
    3.9. Initialize the range of distance.
    3.10. Initialize x and Zo1.
    3.11. Create a 3D figure and axes.
    3.12. Create the animation.
    3.13. Display the plot.
    3.14. End.
```

RESULTS AND DISCUSSION

Oil medium (insulator)

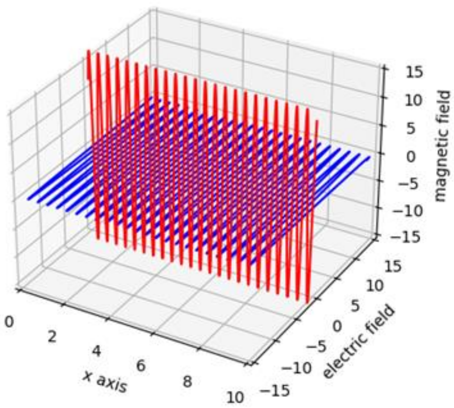

Figure 2. Oil medium (insulator)

Oil, when used as an electrical insulating medium, demonstrates unique electromagnetic properties primarily due to its very low or near-zero conductivity. This low conductivity significantly impedes the conduction of electric current, which, in theory, should result in minimal attenuation of electromagnetic waves as they propagate through the oil. However, the complex relationship between conductivity and wave propagation also suggests that the medium's intrinsic properties contribute to some level of energy absorption and attenuation, albeit minimal (Shi et al., 2019). This nuanced behavior implies that while the waves experience some attenuation, the effect is not substantial enough to drastically reduce wave amplitude over short distances.

In oil, the synchronization of the electric and magnetic fields within electromagnetic waves ensures that these waves maintain a stable amplitude during propagation. This in-phase relationship is critical for the preservation of wave integrity and the prevention of amplitude fluctuations, which could otherwise disrupt signal transmission. Additionally, oil's higher dielectric constant relative to air means that the electromagnetic waves travel more slowly through oil than through air. This reduction in propagation speed is due to the increased permittivity, which affects the wave's velocity according to the relationship between the dielectric constant and the speed of light in the medium.

Moreover, the propagation speed of electromagnetic waves in oil is frequency-dependent, a phenomenon known as dispersion. This means that different frequencies of the electromagnetic spectrum travel at different speeds, leading to the potential spreading out or dispersion of wave packets over time. This dispersion is crucial to understand in applications involving high-frequency signals or broadband transmission, where the integrity of the signal could be compromised if different frequency components arrive at different times. Consequently, while oil serves as an excellent insulating medium with low conductivity and stable amplitude propagation, its higher dielectric constant and dispersive nature necessitate careful consideration in the design and analysis of electromagnetic systems utilizing oil..

Water medium (conductor)

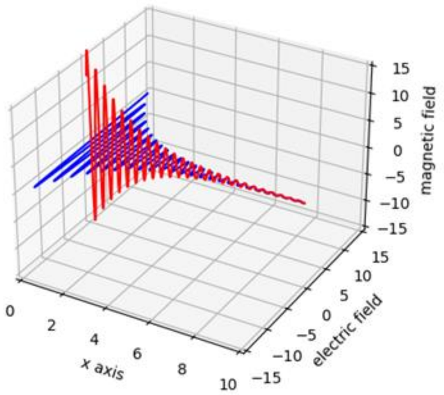

Figure 3. Water medium (conductor)

Water, in contrast to oil, is a superior electrical conductor. This results in electromagnetic waves propagating through water experiencing significant attenuation due to the medium's high conductivity (Wang et al., 2024). Water is particularly adept at absorbing electromagnetic waves, especially at higher frequencies. Due to its non-zero conductivity, electromagnetic waves in water experience a decrease in amplitude over distance.

Water's dielectric constant is considerably higher than that of air, leading to a slower propagation speed for electromagnetic waves. Beyond water and oil, other media such as air, soil, and metals also influence electromagnetic wave behavior. Air, with a dielectric constant nearly equivalent to that of a vacuum, allows electromagnetic waves to propagate almost at the speed of light. Soil and metals, each with distinct properties, also significantly impact wave propagation.

By examining the conductivity and dielectric properties of water and oil, this research enhances students' understanding of the behavior of electromagnetic waves in these mediums. The simulations performed provide visual and analytical insights into how electromagnetic waves propagate through water and oil, illustrating the effects of medium properties on wave characteristics. Thus, the 3D visualization method is easier to understand than through traditional methods. In addition, the interactive nature of the 3D model allows students to engage more deeply with the material which can improve retention and a clearer understanding of electromagnetic waves behaving in different circumstances.

CONCLUSION

This research effectively simulated and analyzed the propagation characteristics of electromagnetic waves in diverse media, including water and oil, utilizing the Finite-Difference Time-Domain (FDTD) method. The simulation results highlighted that the disparities in conductivity and attenuation constants among different media, such as water and oil, substantially influence the behavior of electromagnetic waves propagating through these environments.

In oil, an insulating medium with an attenuation constant $\alpha = 0$, electromagnetic waves maintain consistent amplitude and phase during propagation. Conversely, in water, a conductive medium with a specific attenuation constant, the waves experience significant attenuation, resulting in a reduction in amplitude over distance. These findings offer profound insights into the interaction between electromagnetic waves and conductive versus insulating media.

The implications of this research are far-reaching, with practical applications in fields such as underwater communication and oil spill monitoring. By enhancing the theoretical understanding of electromagnetic wave propagation, this simulation also provides valuable guidance for optimizing the performance of devices that utilize these waves across different media.

This research also offers several important benefits to education such as improving student understanding by providing clear visual representations of concepts that are complex and difficult to understand with traditional methods. Interactive 3D models can enhance a more dynamic learning experience. Through this approach it not only helps students recall information more effectively, but fosters a deeper understanding of the material.

This research has great potential to explore the application of 3D visualization to other physics concepts such as quantum mechanics or relativity. In addition, testing the effectiveness of 3D visualization on different students can provide insight into how students have different learning styles. This can help refine the use of 3D visualization to maximize the impact on different students.

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