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Two Dimensional Simulation of Electromagnetic Waves on Metal Materials Using the FDTD Method

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Abstract. It is challenging to picture the physical phenomenon known as electromagnetic wave simulation. The purpose of this work is to model the propagation of electromagnetic waves on a two-dimensional medium. FDTD is a method that is quite relevant to be used in visualizing electromagnetic waves. One can utilise Maxwell's equations to describe discrete electromagnetic waves having TM mode. The simulation is in the form of a Gaussian pulse with the magnetic field H and the electric field E having position and time domains, respectively. The proposed simulation conditions have considered the program's boundary conditions and numerical stability. The differential equation method methodology is used in the FDTD method. The simulation results show that the wave without PML is impeccably reflected, and with PML, the wave is reflected by the material utilized. Materials with high conductivity will make the waves decay and reduce their intensity. This research can be used in the investigation of materials and communication media innovation.

1. Introduction

In 1865, James Clark Maxwell explained the theory of electromagnetic waves in vacuum media and materials. The electromagnetic theory explains the propagation of waves caused by the connection c. One more clarification was advanced by Faraday, who expressed that a changing magnetic field makes a change electric field. Thus, the propagation of electromagnetic waves is mutually perpendicular to the magnetic and electric fields. In different terms, electromagnetic waves will be waves brought about by sped-up moving electric charges and are a combination of electric and magnet fields.

Electromagnetic waves are waves that can be said to be invisible, so they will be challenging to visualize. One method that has been proposed is the Finite Difference Time Domain (FDTD) method. Kane Yee firstly introduced the FDTD method in 1966 to describe the propagation process of electromagnetic waves in free space [1]. The advantages of this method are ease of writing a programming language depending on the time domain of electromagnetic waves and can be visualized. In addition, the FDTD method can analyze integral and differential equations easier than other methods.

The FDTD method, in its application, requires in-depth knowledge bases [2]. This technique has been broadly utilized as a mathematical strategy since 1920 and is regularly used in different fields. This technique has been utilized by a few specialists, mainly concentrating on electromagnetic waves, seismology, radiation and dissipation and the spread of sound waves in acoustic space [3].

One-dimensional FDTD has been studied in various areas, such as hyperthermia [4], dispersive media electromagnetic wave absorption systems [5], and electromagnetic wave impact on biological materials [6]. FDTD can also be used to analyze electromagnetic waves in media with dielectric [7,8] and dispersion media with frequency domain [9]. Then, FDTD was also used for 3-D ADI-R-FDTD modelling in divergence [10]. Another application of FDTD is for the analysis of electric field induction and electron diffraction [11,12]. Meanwhile, industrial FDTD materials are also used to estimate electromagnetic waves in dust plasma [13] and in the telecommunications industry for acoustic and antenna analysis [14,15].

Application 2-dimensional FDTD is required to improve the visualization quality. In 2-dimensional FDTD, it is necessary to apply the theory of perfectly matched layer (PML) for absorption limits [16,17]. One application of 2-dimensional FDTD from previous studies is in anisotropic media [18]. In previous studies, most researchers applied the FDTD method to analyze material properties in one dimension. The utilization of FDTD has not been created and determined to make sense of the variety of permittivity and conductivity in 2 dimensions to see the impact of the field on metals. The proposed research in this study can be utilized for material determination and identifying actual peculiarities related to utilizing electromagnetic waves. The research likewise can be applied to compute the gain and return loss of recieving antenna, particularly microstrip recieving antenna for the Telecommunications area. In this research, the FDTD technique was created in 2 dimensions to see the impact of conductivity and permittivity on the electromagnetic wave in metallic materials.

2. Methods

The proposed research introduces a two-dimensional simulation with the Absorbing boundary condition (ABC) and applies it to Maxwell's equations. The numerical equation for the relationship between the time-dependent electromagnetic radiation fields was formulated by Maxwell [18], the differential equation of a wave propagating in two dimensions can be explained and developed in Equations (1), (2), and (3):

$$\frac{\partial D}{\partial t}=\frac{1}{\sqrt{\varepsilon_0\mu_0}}\nabla\times H \tag{1}$$

$$D(\omega)=\varepsilon_r^*(\omega).E(\omega) \tag{2}$$

$$\frac{\partial H}{dt}=-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\nabla\times E \tag{3}$$

Equations (1) and (2) show the propagation of the divergence of the Gauss for connection among electric and magnet fields. While equation (3) describes the magnetic field strength divergence equation depending on time. For the 2-dimensional simulation, you can choose the wave propagation mode, including transverse magnetic (TM) and transverse electric (TE). If we work in TM mode, then equations (1), (2) and (3) can be equation

$$\frac{\partial D_z}{\partial t}=\frac{1}{\sqrt{\varepsilon_0\mu_0}}\left(\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right) \tag{4}$$

$$D(\omega)=\varepsilon_r^*(\omega).E(\omega) \tag{5}$$

$$\frac{\partial H}{dt}=-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\nabla\times E \tag{6}$$

$$\frac{\partial H}{dt}=-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\nabla\times E \tag{7}$$

Equations (4) to (7) are the TM mode equations of the normalized electric and magnetic field divergence equations.

As in Maxwell's equation for 1-dimension, it is necessary to insert a function spatially for the 2-dimensional equation. The type of differential equation conditions can be modified in various ways for spatial and temporal solutions to electric and magnetic field propagation. Simulation of electromagnetic wave propagation in a medium having conductivity and permittivity can be approximated as follows [19]

$$\frac{D_z^{n+1/2}(i,j)-D_z^{n-1/2}(i,j)}{\Delta t}=\frac{1}{\sqrt{\varepsilon_0\mu_0}}\left(\frac{H_y^n\left(i+\frac{1}{2},j\right)-H_y^n\left(i-\frac{1}{2},j\right)}{\Delta x}\right)-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\left(\frac{H_x^n\left(i,j+\frac{1}{2}\right)-H_x^n\left(i,j-\frac{1}{2}\right)}{\Delta x}\right) \tag{8}$$

$$\frac{H_x^n\left(i+\frac{1}{2},j\right)-H_x^n\left(i+\frac{1}{2},j\right)}{\Delta t}=-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\frac{D_z^{n+1/2}(i,j+1)-D_z^{n+1/2}(i,j)}{\Delta x} \tag{9}$$

$$\frac{H_y^n\left(i+\frac{1}{2},j\right)-H_y^n\left(i-\frac{1}{2},j\right)}{\Delta t}=-\frac{1}{\sqrt{\varepsilon_0\mu_0}}\frac{E_z^{n+1/2}(i+1,j)-E_z^{n+1/2}(i,j)}{\Delta x} \tag{10}$$

From equation (8) to (10), if it is written in the programming language, it is as follows:

$$Dz[i][j] = dz[i][j] + 5 * (hy[i][j] - hy[i-i][j] - hx[i][j] + hx[i][j-l]) \tag{11}$$

$$hx[i][j] = hx[i][j] + .5 * (ez[i][j] - ez[i][j+l]) \tag{12}$$

$$hy[i][j] = hy[i][j] + .5 * (ez[+1][j] - ez[i][j]) \tag{13}$$

Note that the connection between *Ez* and *Dz* in conditions (12) and (13) is equivalent to the relationship for straightforward lossy dielectrics in the one-layered case. The equations of propagation constants and attenuation that depend on the conductivity and permittivity of the material can be written in equations (14) and (15).

$$\alpha=\frac{\omega}{c_0}\sqrt{\frac{\varepsilon_r}{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_0\varepsilon_r}\right)^2}-1\right]^{1/2} \tag{14}$$

$$\beta=\frac{\omega}{c_0}\sqrt{\frac{\varepsilon_r}{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon_0\varepsilon_r}\right)^2}+1\right]^{1/2} \tag{15}$$

The initial assumption that needs to be set in the FDTD simulation, especially for the speed of electromagnetic waves in a vacuum, cannot be faster than the speed of light. Determination of the time interval using FDTD stability in n-dimensional bias written in equation (16) can be used to solve the problem [20].

$$\Delta t\le\frac{\Delta x}{\sqrt{n}c_0} \tag{16}$$

Provision of essential boundary conditions to avoid reflection of electromagnetic waves, especially electric fields (*E*) and magnetic fields (*H*) in n-dimensional. Mathematically, the FDTD technique on the electric field E is obtained by considering the value of the magnetic field [20]. The hypothesis that makes sense of the limit conditions is known as the Hypothesis of Retaining Limit Conditions (Theory of ABC). In boundary condition theory, it is necessary to consider the values on both sides [21].

According to the theory, it would be more profitable if the electromagnetic waves in the boundary plane had to spread outward because there were no sources outside the boundary. This fact is used to calculate the value at the boundary based on the quantity of area. Electromagnetic waves will propagate to the limit at the speed of light, just like in free space. The shift of the electromagnetic wave position in FDTD can be written as equation (17).

$$\text{displacement} = \frac{\Delta x}{2} \tag{17}$$

Computer resources determine the speed of the FDTD simulation. The wave generated from the source is a point spread in free space, and unpredictable reflections are possible. ABC theory distinguished between incident waves and reflected waves. During the FDTD loop process, ABC theory becomes the right solution to solve complex problems. The development of the Perfect Match Layer (PML) theory by previous researchers is used to increase flexibility [21].

3. Results and Discussion

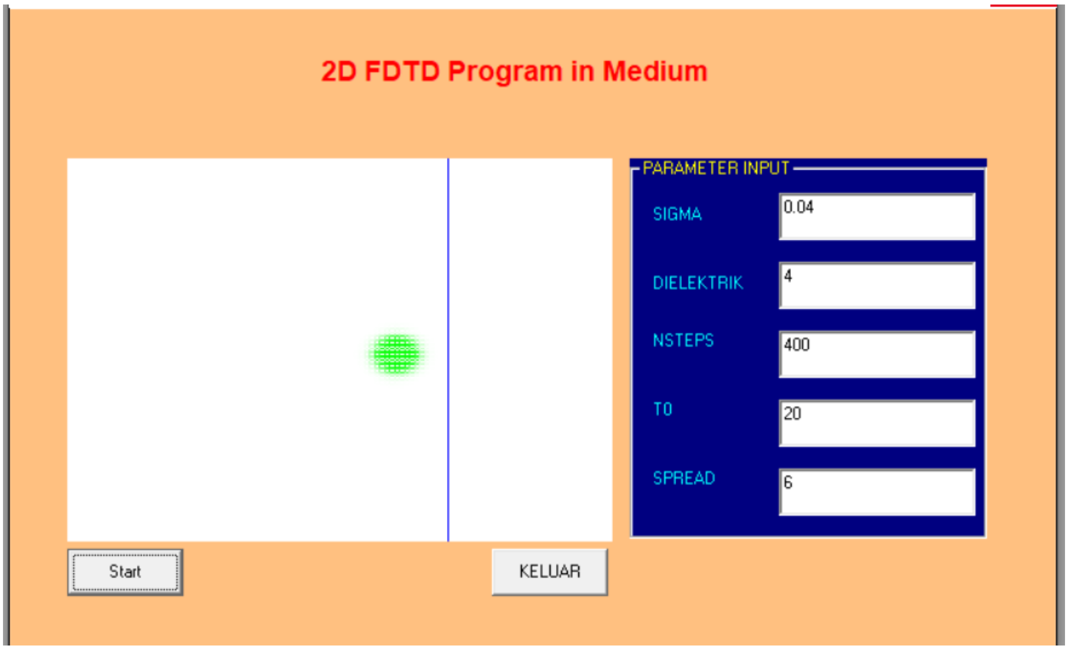
Figure 1 depicts a visual form of the proposed 2D FDTD simulation for expressing electromagnetic waves in a dielectric medium. The input parameters include conductivity, permittivity, NStep, initial time T0, and spread. Initial parameter values for inputs include conductivity 0.04 C/m^2, dielectric 4, NStep 400, initial time 20 and spread 6.

The visualization display in Figure 1 shows that the left side of the blue line is the free space field, and the right side is the medium field. Electromagnetic waves are depicted in a green circle contour with radial propagation. The programming language for electromagnetic waves in the form of a circle can be written as follows:

```
For JJ = 0 To JE / 2
    For ii = 0 To IE / 2
      i = 2 * ii: j = 2 * JJ
      On Error Resume Next
      Picture1.Circle (i, (200 - (j))), 1, RGB(255 - 3 * ez(i, j), 255, 255 - 3 * ez(i, j))
      Picture1.Line (150, 0)-(150, 300), vbBlue
    Next ii
  Next JJ
```

While the pulse form used is a Gaussian wave with an electric field amplitude of 400 N/C. The form of writing the programming language for the looping process of electric and magnetic fields as well as pulse components can be written as follows:

```
For n = 0 To nsteps
T = T + 1
  For j = 1 To IE
    For i = 1 To JE
      dz(i, j) = dz(i, j) + 0.5 * (hy(i, j) - hy(i - 1, j) - hx(i, j) + hx(i, j - 1))
    Next i
  Next j
  pulse = 400 * Exp(-0.5 * ((t0 - T) / spread) ^ 2)
```


2D FDTD Program in Medium

PARAMETER INPUT
SIGMA 0.04
DIELEKTRIK 4
NSTEPS 400
T0 20
SPREAD 6

Figure 1. FDTD 2 D program display

Figure 2 shows that the pulses of electromagnetic waves propagate radially and spread evenly in all directions before passing through the medium. Electromagnetic waves in free space have a wave speed proportional to the velocity of light [20].

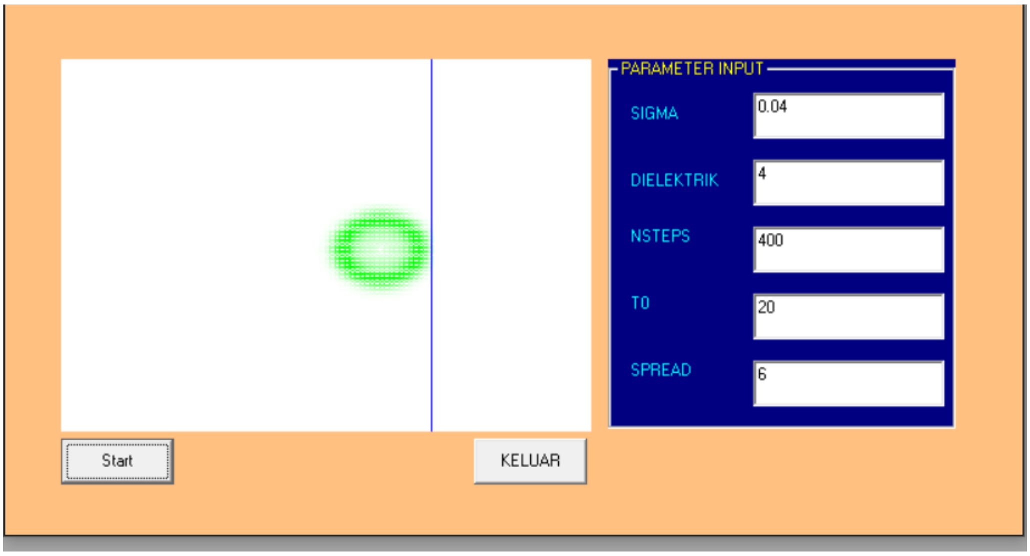

PARAMETER INPUT
SIGMA 0.04
DIELEKTRIK 4
NSTEPS 400
T0 20
SPREAD 6

Figure 2. Electromagnetics wave when entering the medium

The calculation results show that the attenuation value in equation (14) ranges from 3.7344977 Np/m. The value of the propagation constant, as shown by equation (15), shows 29.54364880 rad/m. After passing through the metal surface because of attenuation, the wave decays according to previous studies [8], as shown in Figure 3.

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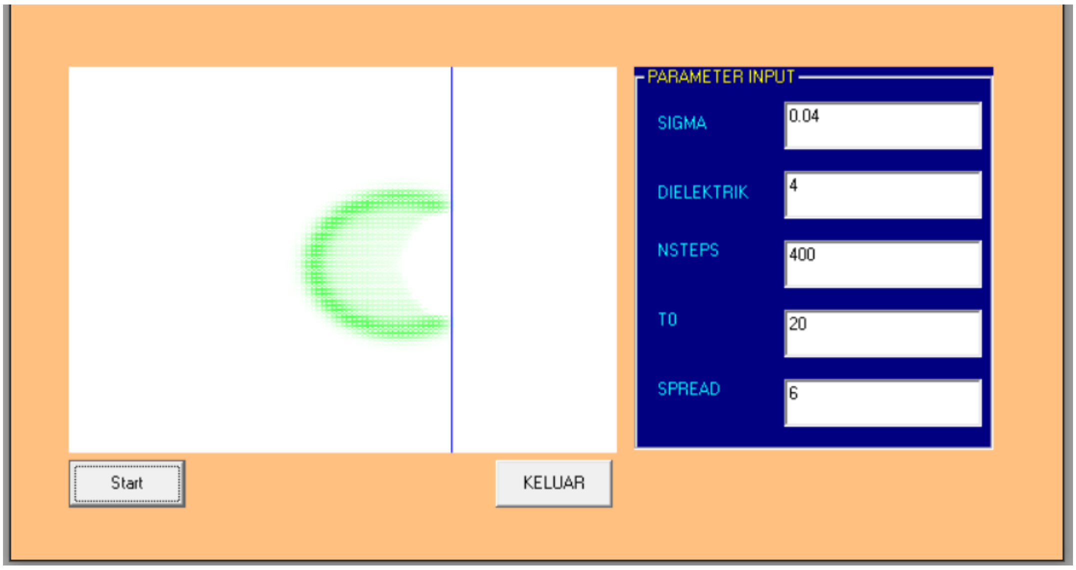
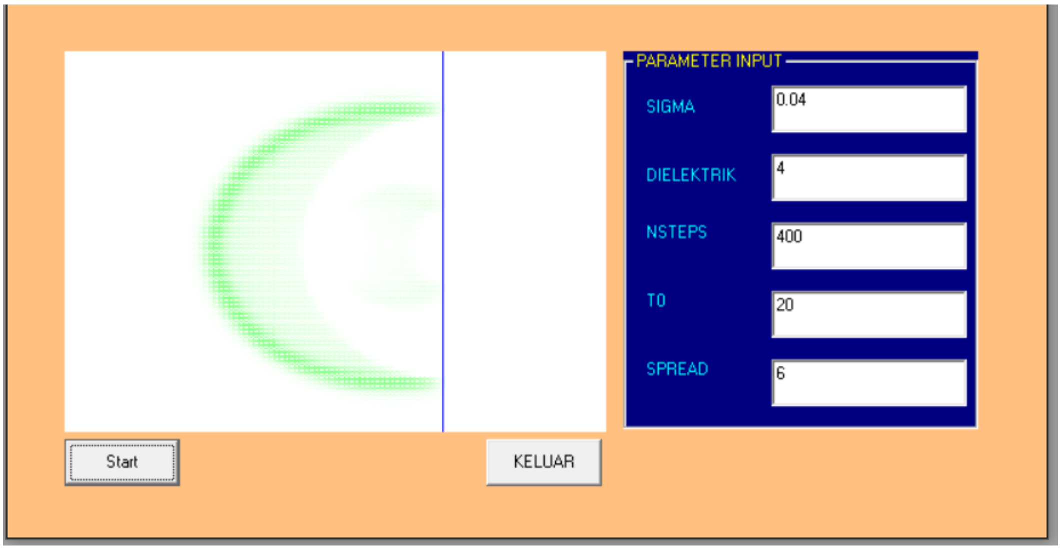


SIGMA 0.04
DIELEKTRIK 4
NSTEPS 400
T0 20
SPREAD 6

Figure 3. Electromagnetic waves after entering the medium



SIGMA 0.04
DIELEKTRIK 4
NSTEPS 400
T0 20
SPREAD 6

Figure 4. Reflection of electromagnetic waves on the medium

Figure 3 simulates how the Gaussian pulse formed in an electromagnetic wave begins to attenuate and propagate. In Figure 3, reflections of the *Ex* and *Hy* field components start due to the wave's phase change. The spread outcomes in the medium show a similar stage and experience lessening, so the waveform decay is as in the past review [22]. The reduction in intensity or energy causes the decay of electric and magnetic fields due to the assimilation of energy by the permittivity of metallic materials. Previous research has not shown a phenomenon like this [20].

Figure 4 simulates reflections in electromagnetic waves in the form of Gaussian pulses due to metal permittivities of 4. The resulting reflection undergoes a phase change between the incident field wave and the reflected one. This reflection phenomenon is influenced by the value of attenuation and wave propagation. The value of propagation and damping can be calculated by equations (14) and (15). These results are supported by previous studies in 1 dimension of metal plates [22].

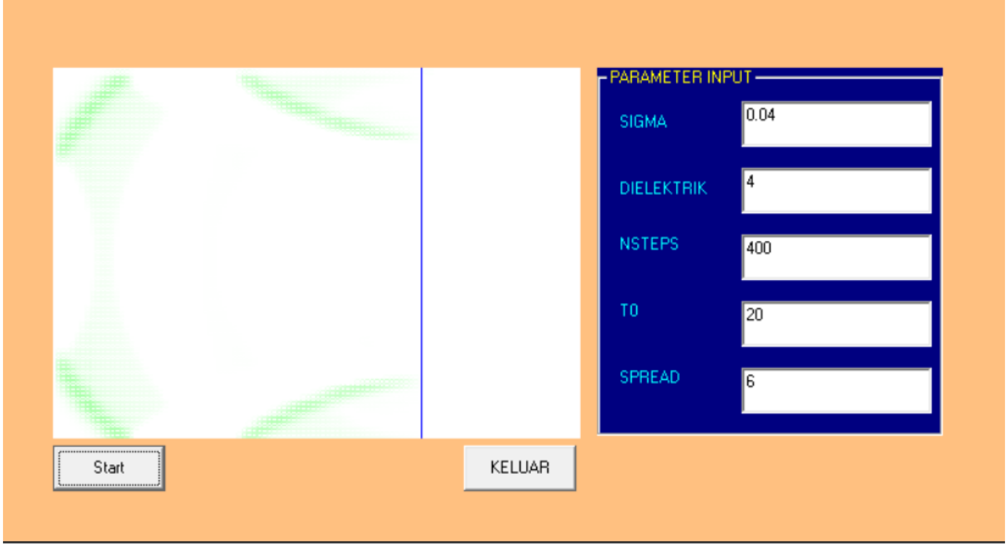

PARAMETER INPUT
SIGMA 0.04
DIELEKTRIK 4
NSTEPS 400
T0 20
SPREAD 6

Figure 5. Electromagnetics simulation without PML

Figure 5 shows the simulation results of electromagnetic waves without Perfect Match Layer (PML) on the top, bottom and left side walls. It illustrated that without PML, the wave is perfectly reflected like a mirror. It indicated how necessary to apply ABC theory. The simulation results show that the wave superposition decreases in the *Ex* field component while it increases in the *Hy* field component due to the permittivity value. The advantage of this 2-dimensional simulation model is that the pulse shape and wave reflection symptoms are more visible. The impact of this proposed research, among others, is to see the waveform physically on the media, both the influence of the permittivity and the conductivity. The limitation of this study is that further experiments are needed to validate the proposed simulation.

4. Conclusion

In the research, the 2-dimensional wave propagation has been simulated using metal as the media. The simulation results show that the permittivity and conductivity properties affect the waveform of the metal, both reflected and transmitted. The permittivity value affects the *Ex* and *Hy* field components to have a different direction of superpositions between transmitted and reflected waves. As a result of permittivity, the *Ex* components are destructive, while the *Ey* components are constructive. On the other hand, the field components *Ex* and *Hy* decay faster due to the conductivity value.

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