Matlab Simulation of Electromagnetic Waves Propagation Characteristics

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Abstract. Military technology has developed rapidly in recent years and used widely in marine communications, maritime aviation, and underwater exploration. With the rapid development of signal processing and antenna technologies, underwater electromagnetic communication has received much attention. Since water is a conductive medium, characteristics exhibited by electromagnetic waves in water are fundamentally different from those in oil. In order to better study the propagation characteristics of electromagnetic waves within the medium, the simulation of the electromagnetic wave propagation in water and oil were conducted using MATLAB, and variation of the electric field and magnetic field vector with time were obtained. Moreover, the three-dimensional real-time graphics of electromagnetic wave propagation can also be simulated in MATLAB; different patterns of electromagnetic waves propagating in oil and water were generated.

1. Introduction
The transportation and exploitation of offshore oil have developed rapidly in recent years. The study of underwater electromagnetic wave is conducive to the development of oil spill monitoring and oil film thickness measurement technology, which also comes along with great prospect on application. At present, research on marine oil spill monitoring at home and abroad has been continuously developed, and many monitoring programs have been proposed. Many of them use electromagnetic related knowledge to solve marine oil spill problems. The oil film thickness measured by electromagnetic wave is easily affected by sea breeze and wave. In order to provide a more accurate measurement method, this paper discusses in detail the difference of conductivity between seawater and various oils and the propagation characteristics of electromagnetic waves in seawater, and analyses the causes and propagation rules of the differences in the propagation of electromagnetic waves in different media.
2. **Seawater conductivity**

Conductance per unit length of a water column with cross-sectional area of a square centimeter is termed as ‘liquid conductivity’. Natural water source, such as rain, tap water, underground water, river, lake and sea water, etc., contains different concentrations of electrolytes. Electrolytes are conductive ions with positive and negative charges, such as H\(^+\), K\(^+\), I\(^-\), OH\(^-\), Na\(^+\). When an electric field is applied across electrodes in the aqueous solution, ions movement forms an electric current under the effect of electric field. This is the conductive property of water, and this property can be described by the conductivity (or resistivity) of water. Seawater contains more than ten times conductive ions than rivers and lakes, so the conductivity of seawater is much higher. Experts and scholars such as Xueyi Min and Guohua Chen studied the relationship between the conductivity, chlorine and density in water samples offshore in China, the conductivity of these water samples were between 48.5-68.7. For air conductivity, the average surface conductivity of the global surface atmosphere is 2.3×10\(^{-14}\), with variation between 0.2×10\(^{-14}\) and 6×10\(^{-14}\). It can be seen that the conductivity of seawater is much greater than the conductivity of sea surface air. Compared with the conductivity of seawater, the conductivity of air is negligible. Most of the conductive medium in petroleum are hydrocarbons, and there are also a small number of non-hydrocarbons and sulfur compounds. These light and non-hydrocarbon compounds are insulating materials. Therefore, oil and oil products have strong insulation, Electrical resistivity of various oils are shown in Table 1.

| Oil Products               | Resistivity / Ω.m | Oil Products | Resistivity / Ω.m |
|---------------------------|-------------------|--------------|-------------------|
| Insulating Mineral Oil    | 10\(^{11}\)-10\(^{17}\) | Aviation kerosene | 2.1×10\(^{12}\) |
| Purification Of Hydrocarbons With High Purify | 1×10\(^{15}\) | Diesel | 1.3×10\(^{12}\) |
| Light Fraction            | 10\(^{10}\)-10\(^{14}\) | gasoline | 2.5×10\(^{11}\) |
| Petroleum Ether           | 8.4×10\(^{12}\) | crude | 10\(^{-14}\) |
| Kerosene                  | 7.3×10\(^{12}\) |              |                   |

Since the seawater conductivity is about 3S/m, σ≠0, lossy conductive medium, and the propagation constant is complex, thus causing the magnetic field and electric field to be out of phase and their amplitudes to be continuously attenuated.

In air, the average total surface conductivity of the global surface atmosphere is 2.3×10\(^{-14}\), varying between 0.2×10\(^{-14}\) and 14-6×10\(^{-14}\), in vacuum, uniform lossless medium, σ=0

Most of the conductive medium in various oils are hydrocarbons, and there are also a small number of non-hydrocarbons and sulfur compounds. These light and non-hydrocarbon compounds are insulating materials, so various oils after separation are very strong, and 10\(^{-5}\) can be considered as 0, so σ=0 in oil is uniform and no coal consumption.

In an ideal uniform isotropic space, the magnetic field and electric field of the plane electromagnetic wave are perpendicular to each other, in the same phase, and the amplitude remains unchanged without attenuation.

3. **The propagation characteristics of electromagnetic waves in uniform and lossy media**

When the electromagnetic wave propagates in a medium with conductivity σ, and with relative dielectric constant \( \varepsilon = \varepsilon_r \varepsilon_0 \), and magnetic permeability \( \mu = \mu_r \mu_0 \), the wave satisfies the Maxwell's equations.

\[
\nabla \times \mathbf{H} = \varepsilon \mathbf{E} + j \omega \varepsilon_0 \mathbf{E} = j \omega \varepsilon_0 \mathbf{E} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \tag{2.1}
\]

\[
\nabla \times \mathbf{E} = -j \omega \mu \mathbf{H} = -\mu \frac{\partial \mathbf{H}}{\partial t} \tag{2.2}
\]

\[
\n\nabla \cdot \mathbf{B} = 0 \Rightarrow \nabla \cdot \mathbf{H} = 0 \tag{2.3}
\]
\[ \nabla \cdot \vec{D} = 0 \Rightarrow \nabla \cdot \vec{E} = 0 \quad (2.4) \]

\[ \vec{B} = \mu \vec{H}, \vec{D} = \varepsilon \vec{E} \]

Where \( \varepsilon_e = \varepsilon - j \frac{\sigma}{\omega} \) is the equivalent dielectric constant, when \( \sigma = 0 \), that is, when the medium is a lossless medium, \( \varepsilon_e = \varepsilon \). For a linear (\( \vec{D} \) Parallel to \( \vec{E} \), \( \vec{B} \) Parallel to \( \vec{H} \)), uniform (the same performance for all dot media) and isotropic (\( \mu \) and \( \varepsilon \) and direction-independent) medium (abbreviated as LHI media), \( \mu \) and \( \varepsilon \) are standard constants. Such a medium is also referred to as a homogeneous medium.

The above equations are only dependent on two variables (\( \vec{E} \) with \( \vec{H} \)) related. We can then derive an equation with variable \( \vec{E} \) from equation (2.2)

\[ \nabla \times \nabla \times \vec{E} = -\mu \nabla \times \left( \frac{\partial \vec{H}}{\partial t} \right) \quad (2.5) \]

Substituting vector identities \( \nabla \times \nabla \times \vec{E} = \nabla (\nabla \cdot \vec{E}) - \nabla^2 \vec{E} \) and \( \nabla \times \vec{E} = 0 \) into \( \nabla \times \nabla \times \vec{E} = \nabla^2 \vec{E} \) into Equation (2.5), and computing the vector in Cartesian coordinates

\[ \nabla^2 \vec{E} = \nabla^2 E_x \hat{a}_x + \nabla^2 E_y \hat{a}_y + \nabla^2 E_z \hat{a}_z \quad (2.6) \]

The Laplacian operator in (2.6) is

\[ \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (2.7) \]

Changing the order of differentiation, formula \( \nabla \times \nabla \times \vec{E} = -\mu \nabla \times (\frac{\partial \vec{H}}{\partial t}) \) can be rewritten as

\[ \nabla^2 \vec{E} = \mu \sigma \frac{\partial \vec{E}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (2.8) \]

\( \nabla \times \vec{H} \) can be substituted using Equation (2.1) to get

\[ \nabla^2 \vec{E} = \mu \sigma \frac{\partial \vec{E}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (2.9) \]

This is a set of three equations in the conductive medium with field \( \vec{E} \). We can obtain a similar set of three equations for \( \vec{H} \),

\[ \nabla^2 \vec{H} = \mu \sigma \frac{\partial \vec{H}}{\partial t} + \mu \varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \quad (2.10) \]

The set of six independent equations given by equations (2.9) and (2.10) are called the general wave equations. These equations govern the behavior of electromagnetic fields in homogeneously conductive medium. In second-order differential equations, the existence of the first-order term indicates that the field is attenuated (with energy loss) as it propagates through the medium. Therefore, the conductive medium is called a lossy medium.

The wave equation of electromagnetic waves in the medium is

\[ \nabla^2 \vec{E} + y^2 \vec{E} = 0 \quad (2.11) \]
\[ \nabla^2 \vec{H} + y^2 \vec{H} = 0 \quad (2.12) \]

Where \( \gamma = \omega \sqrt{\mu \varepsilon} \), the propagate constants. The propagation equation of the electromagnetic wave (assuming the propagation direction is z) is

\[ \vec{E} = e_x E_m e^{-\gamma z} = e_x E_m e^{-az} e^{-j\beta z} \quad (2.13) \]
\[ \vec{H} = e_z \times \vec{E} = e_z \mu \varepsilon_m e^{-az} e^{-j\beta z} \quad (2.14) \]

Where \( \omega (\mu \varepsilon)^{1/2} = \omega [\mu(\varepsilon - j \frac{\sigma}{\omega})]^{1/2} = \alpha + j\beta \)

\[ \alpha = \omega \mu \varepsilon^{1/2} \left[ 1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2 \right]^{-1} \]
\[ \beta = \omega \mu \varepsilon^{1/2} \left[ 1 + \left( \frac{\sigma}{\omega \varepsilon} \right)^2 \right]^{1} \]

Where \( \alpha \) is the decay constant and \( \beta \) is the phase constant.

When the medium is a uniform, non-consuming medium, the attenuation constant \( \alpha = 0 \), the phase constant \( \beta = \omega \sqrt{\mu \varepsilon} \). From the above analysis, it can be seen that the propagation characteristics of
electromagnetic waves in a uniform, lossy conductive medium ($\sigma \neq 0$, such as water, a conductor) and the propagation characteristics in a uniform lossless medium ($\sigma = 0$, such as vacuum or oil) are different. When the electromagnetic wave propagates in the lossless medium, the attenuation constant $\alpha = 0$, the electromagnetic wave does not decay during the propagation process; when the electromagnetic wave propagates in a conductive medium, the attenuation constant $\alpha \neq 0$, the electromagnetic wave is attenuated during the propagation process.

In oil, the magnetic field and the electric field are in phase, the amplitude remains the same, and no attenuation occurs. In water, since the conductivity is not zero, the propagation constant is complex, resulting in a phase difference between the magnetic field and the electric fields with a continuously attenuated amplitude. We then simulated the two cases using Matlab.

The simulation codes are as follows:

```matlab
clear;
cle
k=2*pi;% spatial propagation constant
w=10;% angular frequency
Exm=20*sqrt(2); % electric field amplitude
Hym=15*sqrt(2); % magnetic field amplitude
x=0:0.01:3; % space representative point
Zo1=zeros(size(x));
for i=1:1000
    t=i*0.01;
    % Ey=Exm*cos(w*tk*x);% oil
    % Hz=Hym*cos(w*tk*x);% oil
    Ey=Exm*cos(w*tk*x).*exp(-0.5*x);% underwater
    Hz=Hym*cos(w*tk*x-pi/4).*exp(-0.5*x);% underwater
    figure(1)
    plot3(x,Ey,Zo1,'b');
    hold on;
    plot3(x,Zo1,Hz,'b');
    grid on;
    axis([0,2,-20,20,-20,20])
    Xlabel('x axis'); ylabel('electric field'); zlabel('magnetic field');
    set(gcf,'color','w')
    pause(0.01)
    hold off;
end
```

4. Simulation results

By running the above code, the electric and magnetic field trajectories of electromagnetic waves in water and at different points in the oil can be obtained. Figure 1 shows the trajectories of the electric and magnetic field vectors at three different time in water space. Figure 2 shows the trajectories of the electric and magnetic field vectors at three different time in oil.

The simulation results are as follows:
5. The conclusion

When the electromagnetic wave propagates in a loss-free medium (such as oil), the attenuation constant $\alpha=0$, the magnetic field and the electric field are in phase, the amplitude remains unchanged, and the electromagnetic wave does not decay during propagation; when the electromagnetic wave propagates in a conductive medium (such as water), the attenuation constant $\alpha \neq 0$, the conductivity is not zero, the propagation constant is complex, and the electromagnetic wave is attenuated during propagation.

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