A Preliminary study on air wave separation from Marine CSEM Data by using Fictitious Wave Domain Modelling

Jie Lu 1, Yuguo Li 1,2
1 College of Marine Geo-sciences, Ocean University of China, Qingdao 266100, China
2 Key Lab of Submarine Geo-sciences and Prospecting Techniques of Ministry of Education, Ocean University of China, Qingdao 266100, China

SUMMARY

Frequency domain marine CSEM responses are seriously influenced by the seawater layer. The diffusive Maxwell equations can be transformed into wave equations in fictitious wave domain (FWD) based on the correspondence principle. In fictitious wave domain, the propagation of the EM fields can be analyzed and investigated, and air waves can be separated from the other types of waves.

Keywords: Fictitious wave domain, air wave, marine CSEM, shot gather

INTRODUCTION

The marine controlled-source electromagnetic (CSEM) method is considered as a geophysical tool for offshore hydrocarbon exploration and reservoir prospect evaluation. The marine CSEM method is a low frequency method. Hence the displacement currents are negligible and the governing equation of marine EM fields is the diffusive equation. Recently, the fictitious wave domain (FWD) method has been proposed for marine CSEM simulations (Mittet 2010, 2015). The FWD method transforms the diffusive Maxwell’s equations to a set of hyperbolic equation by the application of the correspondence principle (Hoop 1996). Connections between EM fields in diffusion frequency domain and EM waves in fictitious time domain are thus established. The fictitious EM wave equations can be efficiently solved by using the finite difference time domain (FDTD) method. The resultant EM fields are completely wave-alike (Mittet, 2010) and hence propagate like waves. The propagation behavior and character of the fictitious EM waves have not yet been well investigated.

In this paper, we investigate and analyze the propagation characteristics of the electromagnetic fields in FWD with the use of the wave propagation theory. We simulate marine CSEM responses in the FWD by using the high-order FDTD method with adoption of the complex frequency shifted perfectly matched layer (CFS-PML) boundary condition (Lu et al., 2018). The propagation characteristic of EM waves in the FWD are demonstrated with several numerical examples.

FICTITIOUS WAVE DOMAIN TRANSFORMATION

Assuming a time variation $e^{-i\omega t}$, the frequency domain Maxwell equations in the quasi-stationary approximation are

$$\nabla \times \mathbf{H}(\omega) - \sigma \mathbf{E}(\omega) = \mathbf{J}(\omega), \quad (1)$$
$$\nabla \times \mathbf{E}(\omega) - i\omega \mu \mathbf{H}(\omega) = 0, \quad (2)$$

where $\omega = 2\pi f$ is angular frequency, $\mathbf{J}$ is electric current density and $\sigma$ is conductivity.

Mittet (2010) defined the fictitious dielectric permittivity $\varepsilon'$ and the fictitious angular frequency $\omega'$ as follows

$$\varepsilon' = \frac{\sigma}{2\omega_0}, \quad (3)$$
$$\omega' = (i + 1)\sqrt{\omega \omega_0}, \quad (4)$$

Eqs. (1) and (2) in diffusion frequency domain can then be transformed to a set of coupled hyperbolic partial differential equations in the fictitious wave frequency domain (Mittet 2010, 2015; Kusuda et al., 2014):

$$\nabla \times \mathbf{H}'(\omega') + i\omega \varepsilon' \mathbf{E}'(\omega') = \mathbf{J}'(\omega'), \quad (5)$$
$$\nabla \times \mathbf{E}'(\omega') - i\omega' \mu \mathbf{H}'(\omega') = 0, \quad (6)$$

where $\omega_0$ is a transform factor.

The governing equations in the fictitious wave time domain can be written as:

$$\nabla \times \mathbf{H}'(t') - \varepsilon' \partial_t \mathbf{E}'(t') = \mathbf{J}'(t'), \quad (7)$$
$$\nabla \times \mathbf{E}'(t') + \mu \partial_t \mathbf{H}'(t') = 0, \quad (8)$$

In the homogeneous media without source, $\mathbf{E}'$ and $\mathbf{H}'$ satisfy:

$$\nabla^2 \mathbf{H}'(t') - \mu \varepsilon' \frac{\partial^2 \mathbf{H}'(t')}{\partial t'^2} = 0, \quad (9)$$
$$\nabla^2 \mathbf{E}'(t') - \varepsilon' \mu \frac{\partial^2 \mathbf{E}'(t')}{\partial t'^2} = 0, \quad (10)$$

Eqs. (9) and (10) indicate that EM fields in FWD satisfy the wave equations. The fictitious wave velocity of EM fields

$$c' = \sqrt{\frac{1}{\mu \varepsilon'}} = \sqrt{\frac{2\omega_0}{\mu \sigma}} \quad (11)$$

is a function of both the conductivity and the
transform factor $\omega_0$. For a given model, it is only dependent on $\omega_0$.

EM field in FWD can be transformed back to the frequency domain:

$$E(\omega) = \int_0^T E(t') e^{-i\omega_0 t'} e^{i\omega_0 t'} dt', \quad (12)$$

$$H(\omega) = \frac{2\omega_0}{i\omega} \int_0^T H(t') e^{-i\omega_0 t'} e^{i\omega_0 t'} dt', \quad (13)$$

EM WAVE PROPAGATION PATHS AND SHOT GATHER

We investigate the propagation characteristics of EM fields in the FWD.

Model 1 - The whole space seawater model

Assume that the whole space is full of seawater and the conductivity is 3.25 S/m, and the fictitious wave velocity is 1.768 km/s if $\omega_0 = 2\pi$ (Fig. 1a). There is only the Direct Wave (DW) from the source to the receiver.

Model 2 - A two half-space model

This model contains a layer of infinite seawater, overlaying by the half-space sediments on the bottom. The conductivity of sediments is 1.05 S/m. The marine CSEM data was created by a unit horizontal electric dipole (HED), oriented along the x-axis, located at a height of 100m above the seafloor. The EM receivers are located on the seafloor (Fig. 1b). There are two types of waves: the Direct Wave (DW) and the seabed refracted wave (BRW), traveling from the source downward through seawater incident at the critical angle to the seabed and then along the seabed to the receiver.

Model 3 - A half-space seawater model

It contains a layer of infinite seawater, overlain by the half-space air on the top of it (Fig. 1c). The infinite seawater generates three types of waves: (a) the direct wave (DW); (b) the air refracted wave (ARW), which has been called 'air wave' in the frequency domain; (c) when the wave travelling upward from the source strikes the air-sea interface with an angle other than zero degree, it is reflected off from the air-sea interface, and back the seawater to the receiver. We call it the air reflected wave (ALW). Fig. 2 shows the normalized shot gather for the fictitious horizontal electric component at 0.1 Hz and 1.0 Hz. For comparison, the right-hand side of the theoretical travel time curves is over plotted. One can see that ARW can be separated from DW and ALW for offset larger than 4.0 km. Assuming that the upper limit of the inverse Fourier transform $T=2.2$ s in (12), one can calculate the 'air wave' field.

Model 4 - Three-layer homogeneous seawater model

This model consists of an infinite air and a layer of 1.0 km seawater, overlaying on the half-space sediments (Fig. 1d). Compared to Model 3 (Fig. 1c), Fig. 1d illustrates the two additional waves: the seabed refracted wave (BRW) and multiple waves (MBW), including multiple seabed refracted and reflected waves, initially travelling from source downward/upward to the seabed/sea-air interface. The multiple waves are repeatedly reflected by the two interfaces, before reaching a receiver.

Model 5 - A four-layer reservoir model with infinite seawater

This model consists of an infinite seawater and a thin resistive layer, which is embedded into the seabed sediments (Fig. 1e). Compared to model 2 (Fig. 1b), Fig. 1e illustrates the additional wave: the oil wave (OW), which is related to the top and bottom of the reservoir.

Model 6 - A five-layer reservoir model

This model contains a thin resistive layer (Fig. 1f). Assuming that the conductivity is 3.25 S/m in the seawater, 1.05 S/m in the sediment and 0.01 S/m in the reservoir. The fictitious wave velocity is 1.768 km/s in the seawater, 3.162 km/s in the seafloor sediment and 31.62 km/s in the reservoir layer, if $\omega_0 = 2\pi$, respectively. The fictitious velocity in the reservoir layer is much higher than in the sediment layer. Compared to the three-layer homogeneous seafloor model (Fig. 1d), this model generates multiple oil waves, contributed by the reflections resulted from both the air-sea and seabed interfaces (Fig. 1f).

AIR WAVE SEPARATION

Fig. 3a and b show the amplitude and phase of the horizontal electric field component for six models (Fig. 1) calculated by using the quasi-analytical solution presented in Li and Li (2016). Fig. 3c and d show the amplitude and phase of various types of waves: DW, ALW, ARW, BRW, MBW, OW and MOW.

For marine CSEM surveying, we are interested in OW and MOW. For offset less than 3.0 km, DW and BRW are the primary wave. For offset ranging from 3.0 km to 9.0 km, OW and MOW dominate the response, but BRW, MBW and ARW are not negligible.

CONCLUSIONS

Transforming Maxwell equations into wave equations provides a new possibility for efficient investigating and analyzing the properties of the marine electromagnetic fields. The propagation of the EM fields can be analyzed in the fictitious time domain and each type of waves has its finite velocity and propagation path. And various wave fields can be separated from each other.
ACKNOWLEDGEMENTS
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REFERENCES


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Figure 2. Normalized shot gather of the horizontal electric component for Model 3 (Fig. 1c) at 0.1 Hz and 1.0 Hz.

(A) Amplitude of Various Models

(B) Phase of Various Models

Figure 3. The amplitude (A) and phase (B) of horizontal electric component for models shown in Fig. 1 at 0.1 Hz; Amplitude (C) and phase (D) of various types of waves: DW, ALW, ARW, BRW, MBW, OW and MOW.