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An Efficient Total-Field/Scattered-Field Technique for the Fundamental ADI-FDTD Method

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Abstract—This paper presents an efficient total-field/scattered-field (TF/SF) technique for the unconditionally stable fundamental alternating-direction-implicit (FADI) finite-difference time-domain (FDTD) method. The equivalent current source approach is used to determine the current source on the Huygen's surface. The current sources are implemented in the explicit auxiliary update equations, which can be solved efficiently. Numerical results are presented to validate the TF/SF implementation in the FADI-FDTD method.

I. INTRODUCTION

Scattering of electromagnetic waves on targets illuminated by distance sources is a commonly performed analysis to determine its radar cross section. To approximate such sources, the total-field/scattered-field (TF/SF) technique was developed for the finite-difference time-domain (FDTD) method to introduce the incident plane waves into the domain [1].

Meanwhile, an efficient unconditionally stable fundamental alternating-direction-implicit (FADI) FDTD was introduced to overcome the Courant stability limit of the explicit FDTD method [2].

In this paper, we present an efficient TF/SF technique for the FADI-FDTD. Numerical results will be presented to validate the TF/SF implementation in the FADI-FDTD method.

II. FUNDAMENTAL ADI-FDTD METHOD WITH TF/SF TECHNIQUE

Consider the 3-D conventional ADI-FDTD method including source excitation in compact matrix form as follows:

$$\left(\mathbf{I} - \frac{\Delta t}{2}\mathbf{A}\right) \mathbf{u}^{n+\frac{1}{2}} = \left(\mathbf{I} + \frac{\Delta t}{2}\mathbf{B}\right) \mathbf{u}^n + \frac{\Delta t}{2}\mathbf{s}^{n+p_1} \quad (1a)$$

$$\left(\mathbf{I} - \frac{\Delta t}{2}\mathbf{B}\right) \mathbf{u}^{n+1} = \left(\mathbf{I} + \frac{\Delta t}{2}\mathbf{A}\right) \mathbf{u}^{n+\frac{1}{2}} + \frac{\Delta t}{2}\mathbf{s}^{n+p_2} \quad (1b)$$

where

$$\mathbf{u} = [E_x \ E_y \ E_z \ H_x \ H_y \ H_z]^T \quad (2)$$

and

$$\mathbf{s} = \left[\frac{-1}{\epsilon}J_x \ \frac{-1}{\epsilon}J_y \ \frac{-1}{\epsilon}J_z \ \frac{-1}{\mu}M_x \ \frac{-1}{\mu}M_y \ \frac{-1}{\mu}M_z\right]^T \quad (3)$$

The current sources are implemented for both time steps, i.e., $n + p_1$ and $n + p_2$, for the above scheme.

To improve the efficiency of the conventional ADI-FDTD method, we formulate it into the fundamental form, by eliminating matrix operators $\mathbf{A}$ and $\mathbf{B}$ from the right-hand sides to obtain:

$$\mathbf{v}^n = 2\mathbf{u}^n - \mathbf{v}^{n-\frac{1}{2}} + \frac{\Delta t}{2}\mathbf{s}^{n+p_2} \quad (4a)$$

$$\left(\mathbf{I} - \frac{\Delta t}{2}\mathbf{A}\right) \mathbf{u}^{n+\frac{1}{2}} = \mathbf{v}^n \quad (4b)$$

$$\mathbf{v}^{n+\frac{1}{2}} = 2\mathbf{u}^{n+\frac{1}{2}} - \mathbf{v}^n + \frac{\Delta t}{2}\mathbf{s}^{n+p_1} \quad (4c)$$

$$\left(\mathbf{I} - \frac{\Delta t}{2}\mathbf{B}\right) \mathbf{u}^{n+1} = \mathbf{v}^{n+\frac{1}{2}} \quad (4d)$$

with auxiliary variables

$$\mathbf{v} = [e_x \ e_y \ e_z \ h_x \ h_y \ h_z]^T \quad (5)$$

Referring to (4), it can be observed that the current sources are only implemented in the auxiliary update equations (4a) and (4c). These are explicit update equations which can be solved efficiently. Moreover, the current sources are clearly separated from the implicit main field update equations (4b) and (4d). This results in a simpler and straightforward implementation as the derivative of magnetic current source $\mathbf{M}$ is not required. Therefore, the fundamental ADI-FDTD method is more efficient than the conventional ADI-FDTD method.

A. Equivalent Current Source Approach

Next, we employ the TF/SF technique to realize a plane wave source. This is typically achieved by means of the field-correction approach or the equivalent current source approach. The update equations of both approaches are analytically similar, with the latter approach being much simpler to implement [3], [4]. For brevity, we shall only discuss the equivalent current source approach.

The equivalent current source approach uses the equivalence theorem to determine the equivalent current sources on the Huygen's surface [5]. These fictitious current sources create the required incident fields on the inside and outside of the imaginary closed surface. This also corresponds to field-corrections at the total-field and scattered-field boundary.

Fig. 1. Total-field/scattered-field grid zoning for a plane wave propagating in freespace with z-directed polarization and with different incident directions. (a) $\theta = 90^\circ$ and $\phi = 90^\circ$. (b) $\theta = 45^\circ$ and $\phi = 45^\circ$.

Subsequently, the current sources for s^{n+p_1} are given as

$$J_x|^{n+p_1} = \frac{1}{\Delta_y} H_z^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_z} H_y^i|^n \quad (6a)$$

$$J_y|^{n+p_1} = \frac{1}{\Delta_z} H_x^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_x} H_z^i|^n \quad (6b)$$

$$J_z|^{n+p_1} = \frac{1}{\Delta_x} H_y^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_y} H_x^i|^n \quad (6c)$$

$$M_x|^{n+p_1} = \frac{1}{\Delta_z} E_y^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_y} E_z^i|^n \quad (6d)$$

$$M_y|^{n+p_1} = \frac{1}{\Delta_x} E_z^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_z} E_x^i|^n \quad (6e)$$

$$M_z|^{n+p_1} = \frac{1}{\Delta_y} E_x^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_x} E_y^i|^n \quad (6f)$$

and for s^{n+p_2} as

$$J_x|^{n+p_2} = \frac{1}{\Delta_y} H_z^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_z} H_y^i|^{n+1} \quad (7a)$$

$$J_y|^{n+p_2} = \frac{1}{\Delta_z} H_x^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_x} H_z^i|^{n+1} \quad (7b)$$

$$J_z|^{n+p_2} = \frac{1}{\Delta_x} H_y^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_y} H_x^i|^{n+1} \quad (7c)$$

$$M_x|^{n+p_2} = \frac{1}{\Delta_z} E_y^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_y} E_z^i|^{n+1} \quad (7d)$$

$$M_y|^{n+p_2} = \frac{1}{\Delta_x} E_z^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_z} E_x^i|^{n+1} \quad (7e)$$

$$M_z|^{n+p_2} = \frac{1}{\Delta_y} E_x^i|^{n+\frac{1}{2}} - \frac{1}{\Delta_x} E_y^i|^{n+1} \quad (7f)$$

where the superscript “ i ” denotes incident fields.

III. NUMERICAL RESULTS

In this section, we perform some numerical simulations to validate the TF/SF technique for the FADI-FDTD method. Fig. 1 depicts the snapshot of a plane wave propagating in freespace with z-directed polarization. In Fig. 1(a) the incident direction of the plane wave is $\theta = 90^\circ$ and $\phi = 90^\circ$, while in Fig. 1(b) the incident direction of the plane wave is $\theta = 45^\circ$ and $\phi = 45^\circ$. From the figure, it is seen that the plane wave propagates entirely through the total-field region and disappears into the scattered-field region.

Fig. 2. Surface current distribution on a PEC sphere subjected to an incident plane wave of 10 GHz calculated using the FADI-FDTD method with CFLN = 4.

TABLE I
CPU TIME (SECONDS) OF THE FADI-FDTD AND CONVENTIONAL EXPLICIT FDTD WITH TOTAL-FIELD/SCATTERED-FIELD TECHNIQUE

Method	CFLN 1	CFLN 4	CFLN 8
Conventional explicit FDTD	60.24	-	-
Fundamental ADI-FDTD	215.77	53.98	27.42

Fig. 2 illustrates the surface current distribution on a perfect electric conducting sphere subjected to an incident plane wave of 10 GHz calculated using the FADI-FDTD method with CFLN = 4. The radius of the sphere is roughly $1.67 \lambda_0$.

Table I compares the CPU time (seconds) taken by the FADI-FDTD method and the conventional explicit FDTD method with TF/SF technique. The computational domain consists of 100^3 uniform cells truncated with convolutional perfectly matched layer of 10 cell thickness. The programs have been compiled using Microsoft Visual C++ under Microsoft Win7 (32-Bit) operating system, and run on a platform of 3.1 GHz Intel I5 processor with 4 GB RAM. Referring to Table I, it can be observed that the FADI-FDTD method is more efficient than the conventional explicit FDTD method for CFLN = 8, as it requires 54.5% less CPU time.

IV. CONCLUSION

This paper has presented an efficient TF/SF technique for the FADI-FDTD method. Numerical results have been presented to validate the TF/SF implementation.

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