A Hybrid Algorithm for Field-to-line Coupling Analysis above Ground

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***Abstract*—A hybrid algorithm combined parabolic equation (PE) and integral equation (IE) is presented for analyzing electromagnetic field coupling to conducting thin-wires above ground. In this algorithm, PE with alternating direction implicit (ADI) difference technology, is applied to calculate the field above ground, which is used as the excitation of the thin-wires. Combined with spatial interpolation technique, the induced currents on wires are simulated by IE solved via the moment method (MoM). Examples are given to illustrate the correctness of the presented algorithm by comparing the results with those of full-wave method (FWM).**

Keywords—parabolic equation (PE); integral equation (IE); electromagnetic coupling; alternating direction implicit (ADI) difference

I. INTRODUCTION

Research on electromagnetic field coupling to conducting wire structures such as communication cables and power lines, is very important in electromagnetic compatibility (EMC) analysis [1-4]. At present, full-wave numerical methods and equivalent circuit approaches are widely applied to analyze the field-to-line coupling above ground. But in the cases the devices be placed in a complex, large-scale and realistic geographical environment, traditional numerical methods usually suffer a huge number of unknowns, and the approximate circuit approaches are insufficient to be extended to consider the influence of the environments.

This paper presents a new hybrid algorithm, which will be able to handle the coupling problems in a more complicated environment. The PE method, which is widely applied to the large-scale electromagnetic prediction applications [5-8], is used to calculate the external field of the wire structures. Usually, for an arbitrary wire with a radius of much less than a wavelength, besides, far less than its length, can be viewed as thin-wire structures. Hence, the induced currents can be assumed to only flow along the axis direction of the wire. From boundary conditions, IE solved via the moment method (MoM) can be applied to simulate the induced currents on the wires using the excitation provided by PE model. To verify the hybrid algorithm, numerical examples are presented, and the results are compared with those of FWM, i.e. MoM based IE.

This paper is structured as follows: in Section II, PE and IE are briefly reviewed, following the hybrid algorithm. Numerical examples are given in Section III to verify the presented algorithm. Some conclusions are presented in Section IV.

II. PE-IE HYBRID ALGORITHM

PE is derived from the Helmholtz wave equation via separating the forward propagation term and back propagation term. Suppose the paraxial direction of PE is fixed at x axis and time-dependence of field is $e^{-j\omega t}$. In Cartesian coordinates, standard PE can be expressed as

$$\frac{\partial u(x,y,z)}{\partial x}=\frac{i}{2k_0}\left(\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)u(x,y,z), \tag{1}$$

where u is a reduced function related to the filed components; k_0 is the wavenumber in free space.

By introducing an ADI difference technique, the three-dimensional (3-D) problem can be converted into a series of 2-D problems, and the computational costs can be significantly reduced. An ADI scheme of Peaceman-Rachford (P-R) type for standard PE is presented in [9].

$$\begin{cases}\left(1-\dfrac{r_y\delta_y}{4jk_0}\right)u^{n+1/2}=\left(1+\dfrac{r_z\delta_z}{4jk_0}\right)u^n\\[2ex] \left(1-\dfrac{r_z\delta_z}{4jk_0}\right)u^{n+1}=\left(1+\dfrac{r_y\delta_y}{4jk_0}\right)u^{n+1/2}\end{cases}. \tag{2}$$

where $r_y=\Delta x/\Delta y^2$, $r_z=\Delta x/\Delta z^2$, and

$$\delta_y u_{m,l}=u_{m+1,l}-2u_{m,l}+u_{m-1,l}$$
$$\delta_z u_{m,l}=u_{m,l+1}-2u_{m,l}+u_{m,l-1}.$$

By using (2), the fields in the entire computational region can be obtained in an iterative approach when giving initial field and suitable boundary conditions.

For a conducting wire with a radius of a, and a length of l, IE for thin-wire approximation can be written in terms of an electric scalar potential Φ and a magnetic vector potential A_l .

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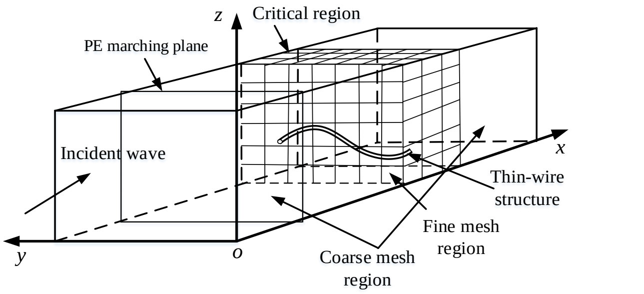

Fig. 1. Hybrid algorithm with non-uniform mesh partitioning technique

$$\overrightarrow{E_l^i} = j\omega A_l + \frac{\partial \Phi}{\partial l} = j\omega\mu\int_l \vec{I}(l)\frac{e^{-jkR}}{4\pi R}dl + \frac{1}{\varepsilon}\frac{\partial}{\partial l}\int_l \rho(l)\frac{e^{-jkR}}{4\pi R}dl. \quad (3)$$

where ρ is charge density and I is the line current on the conductor; μ and ε are permeability and permittivity in vacuum, respectively; R is the distance between the source point and field point.

According to the continuity of the currents, we get

$$\rho = \frac{-1}{j\omega}\cdot\frac{\partial I}{dl}. \quad (4)$$

To obtain the numerical solution of (3), we divide the thin wire into N segments, and the unknown induced currents on the wire can be expressed as a linear combination of N pulse basis functions. It's easy to rewritten (3) in a form of matrix

$$[Z]_{mn}[I]_n = [V]_m, \quad (5)$$

where Z denotes impedance elements; V is the excitation voltage which can be obtained via PE; I denotes the current coefficients.

Note that I_n in (5) can be obtained via matrix inversion with a given excitation provided by PE. Compared with the traditional methods, the hybrid algorithm is applicable for arbitrary excitation source. Besides, it can also take the influence of environments into consideration. To obtain the accuracy fields in the critical region where contains thin-wire structures, a non-uniform mesh partitioning technique combined with spatial interpolation is introduced to connect the mesh points of the two algorithms, which effective reduces the numerical errors caused by mesh interpolation, as shown in Fig.1.

III. Results and Discusssions

In this section, several typical examples are given to verify the correctness of the PE-IE hybrid algorithm. Results are compared with those of FWM. The frequency of the incident plane wave with unit amplitude and y axis polarization, is set to 300 MHz, and the grazing incident angle is 15°. The flat ground is regarded as PEC in this paper. Each wire is divided into 256 segments for single conductor, and 512 for dual-conductor, respectively, and it is enough to make the discretization error small enough.

Fig.2 gives a numerical example of a straight single conductor wire. The amplitude of the induced currents on the conductor is shown in Fig.3. As shown, the result of hybrid algorithm is great consistent with that of full-wave method. Another example of a curved conductor above flat ground is shown in Fig.4. The amplitude of the induced currents on the conductor is shown in Fig.5. It also shows the correctness of the hybrid algorithm.

In addition, Fig.7 shows the simulation result of a dual-conductor, where the two wires at different heights are placed parallel to the ground. As the mutual coupling between two conductors can be characterized by mutual-impedance in IE, it means that no additional effort is required in hybrid algorithm. Results validate PE-IE algorithm in calculation of field-to-line coupling problems for multi-conductor model.

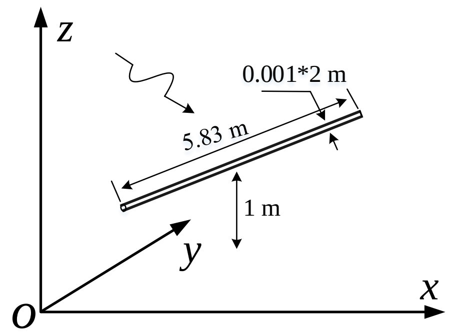

Fig. 2. Model of a straight conductor above flat ground.

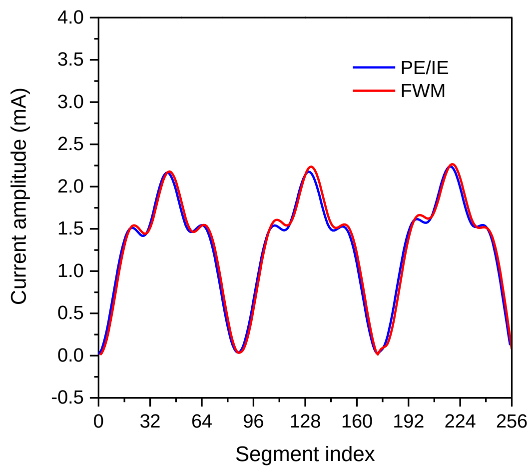

Fig. 3. Amplitude of induced currents on straight conductor.

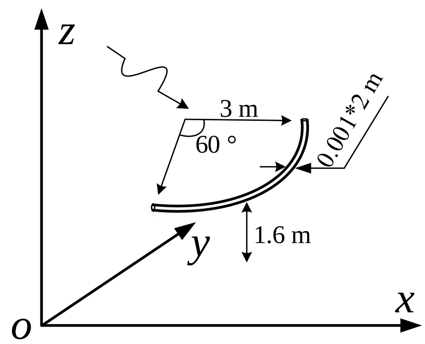

Fig. 4. Model of a curved conductor above flat ground.

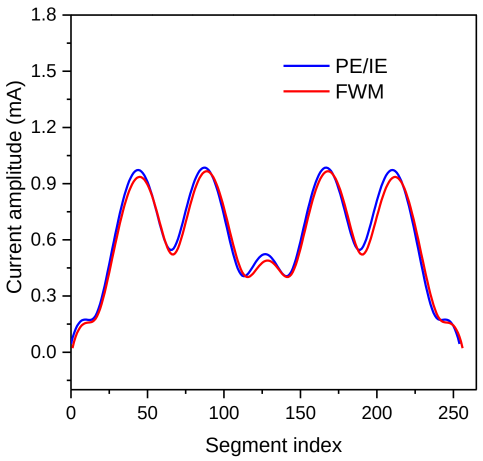

Fig. 5. Amplitude of induced currents on curved conductor.

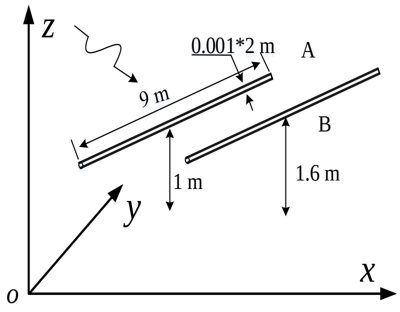

Fig. 6. Model of a dual-conductor above flat ground.

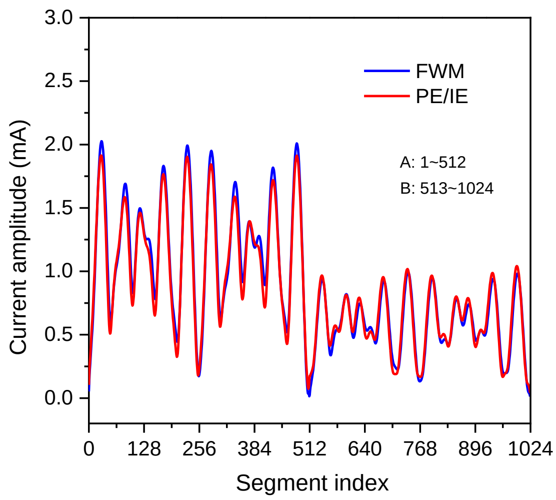

Fig. 7. Amplitude of induced currents on dual-conductor.

IV. Conclusion

In this paper, a hybrid algorithm approach that employs PE and IE, is applied to model field coupling to thin-wire structures. For a preliminary study, the numerical tests show the reliability of the approach. As a regional algorithm with high efficiency and reliable precision, PE can consider the influence of various environments on electromagnetic wave propagation, like irregular terrain, buildings, and atmospheric refraction. Therefore, the present PE-IE hybrid algorithm is expected to simulate the field-to-line coupling problems in a more complex environment. Those work will be discussed in the next study.

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