An Advanced Numerical Technique for Low Frequency Electromagnetic Field Simulation based on Finite-Difference-Time Domain Method

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In this paper, an advanced numerical technique is proposed for the low frequency electromagnetic field simulation. The finite-difference time-domain (FDTD) method is one of the best methods to analyze electromagnetic field problems which require high-precision, such as a heterogeneous whole-body voxel human model. However, directly using the standard FDTD method in the quasi-static frequency band requires an extra-large number of iterations. We overcome this drawback by modifying the FDTD method which employs a quasi-static behavior with the surface equivalence theorem. The results of our method are in good agreement with those from a commercial electromagnetic simulator.

***Index Terms*—Numerical simulation, finite difference methods.**

I. Introduction

RECENTLY, the interest in the harmful influence of the electromagnetic field has increased since lots of electronic equipment uses the wireless power transmission and communication. The finite-difference time-domain (FDTD) method is widely used to simulate computationally complex problem such as a high-resolution voxel human model as it does not include a complex matrix calculation.

However, the standard FDTD method is not suitable for low frequency electromagnetic field simulation because of the increasing of simulation time. Some studies have been conducted to avoid that problem, and those methods have computed field distribution partially [1-3]. However suitable numerical technique for the entire problem has not been developed yet.

We overcome this problem by applying surface equivalence theorem to the quasi-static FDTD. We named our method as surface-equivalence-theorem-based quasi-static FDTD (SQ-FDTD). In this study, the field distributions of a dipole antenna are calculated by commercial software package (FEKO [4]). The entire field can be obtained after applying the FEKO results to the SQ-FDTD. The electric fields inside and outside of a dipole antenna are simulated with the SQ-FDTD method. And the results are compared to FEKO to verify our approach.

II. SQ-FDTD

The FDTD method is a numerical analysis technique which discretizes the time-dependent Maxwell's equations using central-difference approximations to the space and time partial derivatives. The method must satisfy Courant stability condition since it is solved in time domain [5]. Therefore, the time step is dependent on the following:

$$\delta_t = \frac{\Delta}{\sqrt{3} \cdot c_0} \tag{1}$$

where δ_t is the time step, Δ is the space step, c_0 is the speed of light. The simulation time is excessively needed at the low frequencies from this condition. For example, the time step is determined about 2 [ps] by (1) for a mesh grid with $\Delta = \Delta x = \Delta y = \Delta z = 1$ mm that is usually used in the human voxel model. The simulation requires 3.5×10^{10} iterations for analyzing 60 Hz source excitation. In fact, it is impossible to solve as it takes few years to simulate that problem.

SQ-FDTD has been proposed to address this problem. The proposed method is composed of two parts.

The first part includes 4 steps. The first step is arranging arbitrary surface surrounding sources and/or scatters. The shape of surfaces, such as circular, rectangular, cylindrical or spherical shape, is usually selected to reduce a calculation complexity. Then proper numerical technique is selected. Any kind of numerical methods can be used such as method of moment, finite element method, and FDTD method. It depends on the characteristics of the scatterer inside of an equivalent surface. Next, the electric and magnetic currents on the surfaces are obtained by the chosen numerical technique. These currents are inserted to the FDTD method as sources on the equivalent surface. Simple Fourier transforms are applied if calculated currents are in the frequency domain.

$$\overrightarrow{J_s} = \overrightarrow{J_s} \sin(\omega t + \phi) \tag{2}$$

Finally quasi-static behavior is employed to the calculated currents. In the quasi-static steady state, the electromagnetic fields which exist outside of the object are in phase with the incident wave, and the fields inside of the subject are in phase with the time derivative of the phase of the incident wave. Therefore, the iteration process is quickly converged when approximating sinusoidal wave as a ramp function. The modified electric current is expressed as follows [3]:

$$E_{inc} = \begin{cases} 0 & -\infty < t < t_0 \\ (t-(\tau/\pi)\sin(\tau t/\pi))/2 \ (1 & t_0 < t < \tau \\ t-\tau/2 & t > \tau \end{cases} \tag{3}$$

Entire electromagnetic fields are calculated much faster than they are with conventional methods since the quasi-static system converges in much less than one full cycle.

The second part is calculating standard FDTD method with the currents on the equivalent surface as a source.

III. RESULT AND ANALYSIS

The coordinate system for the equivalent surface and sphere in this paper is shown in Fig. 2.

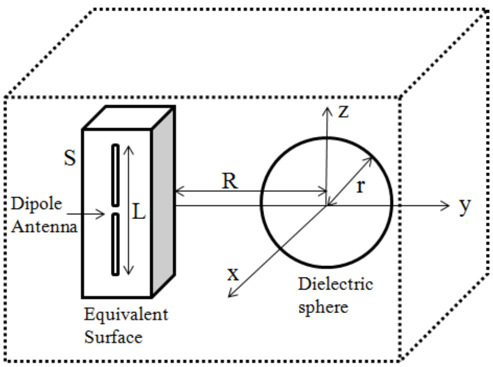


Fig. 2. Simple system for calculating interior and exterior electromagnetic field of sphere from dipole antenna radiation.

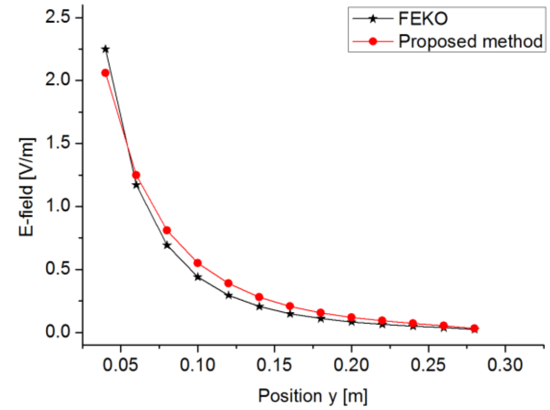
The specifications used in Fig. 2 are summarized in Table 1.

TABLE I
SPECIFICATIONS OF ANALYSIS MODEL

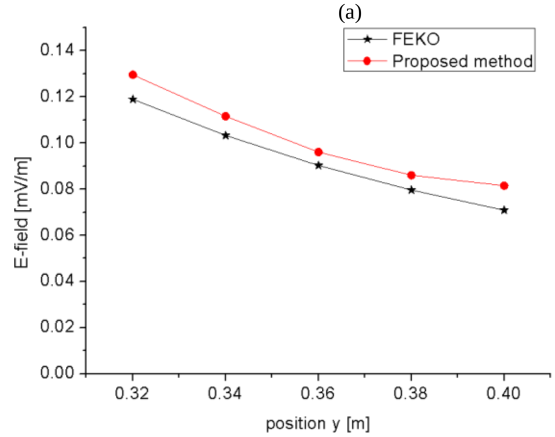
ITEM	Value
Operating frequency (MHz)	1
Total number of FDTD cells	40, 40, 40
Number of Equivalent surface	4,4,14
Equivalent surface center location	10,20,20
$\Delta\ (mm), \Delta t\ (ps)$, τ	20, 0.33, 100Δt
Dipole length (mm)	200
Sphere properties	σ=0.3 S/m, ϵ_r=30, r=60 mm
Sphere center location	30, 20, 20

The transient response decays sufficiently after 600 time steps. After the numerical derivative procedure, all field responses are obtained. The proposed method is in good agreement with the commercial software used (FEKO), as shown in Fig. 3.

The proposed method reduces the simulation time by nearby 200-fold compared to the standard FDTD method. The absolute electric field results from the proposed method are also in good agreement with FEKO in other regions and the much lower frequencies as well. The proposed method becomes even more powerful when the target frequency decreases because required iterations of the standard FDTD method are inversely proportional to the frequency increase, whereas those of the proposed method are not depending on the changing in the frequency under the quasi-static condition.



(a)



(b)

Fig. 3. Simulation *result* (x=z=0, y-axis).
a Electric field outside of the sphere
b Electric field inside of the sphere

IV. CONCLUSION

In this paper, the SQ-FDTD method is proposed. The method is well suited for a heterogeneous dielectric and conductive body with complexly shaped scatterers. The electromagnetic field in and around the dielectric sphere is calculated from the dipole antenna excitation to validate our method. The method has successfully shown the possibility of analyzing near-field problems under low frequencies.

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