CALCULATION OF ELECTRIC FIELDS AND CURRENTS INDUCED IN A MILLIMETER-RESOLUTION HUMAN MODEL AT 60 Hz USING THE FDTD METHOD WITH A NOVEL TIME-TO-FREQUENCY-DOMAIN CONVERSION

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Abstract

The finite-difference time-domain (FDTD) method has previously been used to calculate induced currents in anatomically based models of the human body at frequencies ranging from 20 to 915 MHz and resolutions down to 1.31 cm [1]. Calculations at lower frequencies and higher resolutions have been precluded by the huge number of time steps which would be needed to run these simulations in the traditional way. This paper describes a new method used to overcome this problem and calculate the induced currents in a MRI-based 6-mm-resolution human model at 60 Hz. A new algorithm based on solving two equations with two unknowns is used for calculating magnitude and phase from the CW FDTD simulation. This allows magnitude and phase calculations to be made as soon as steady-state is reached, which is within a fraction of a cycle. For incident electric fields of 10 kV/m, local induced current densities above 16 mA/m^2 have been calculated in the torso, with even higher values up to 65 mA/m^2 for the legs. These are considerably higher than the 4 or even 10 mA/m^2 that have been suggested in the safety guidelines [10].

Introduction

The finite-difference time-domain method has been used extensively for analyzing steady-state frequency-domain behavior in numerous applications. Specific absorption rate (SAR) [1], radar cross section [2], current distribution [3], and S-parameters [4] are a few of the frequency-domain parameters calculated using the FDTD method. Since FDTD is a time-domain method, some conversion must be made from the time to frequency domains. Traditionally this is done with either a peak detection method or a Fourier transform method. Both of these methods require a large amount of computer time and memory, and require that the simulation be run at least half a cycle after convergence has been reached. For applications such as finding the complete current distribution within the human body, these time-to-frequency-domain calculations require as much memory and more computer time than the FDTD simulation itself. This paper describes an alternative to these traditional time-to-frequency-domain calculations which virtually eliminates the computer time required and can dramatically reduce or eliminate the storage requirements as well.

Novel Two-Equation Two-unknowns Time-to-Frequency-Domain Calculations

At a given location in space we can write

$$A \sin(\omega t_1 + \theta) = q_1$$
$$A \sin(\omega t_2 + \theta) = q_2$$

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where A is the amplitude, θ is the phase angle ω (= 2 πf) is the angular frequency. At two times, t_1 and t_2, the values q_1 and q_2 are obtained from the FDTD simulation. Therefore, these equations can be solved for the unknowns, A and θ, to give direct relationships for these values

$$\theta = \tan^{-1} [q_2 \sin(\omega t_1) - q_1 \sin(\omega t_2) + q_1 \cos(\omega t_2) - q_2 \cos(\omega t_1)]$$

$$A = |q_1/\sin(\omega t_1 + \theta|$$

Double precision should be used for accuracy, even if the rest of the FDTD simulation is single precision. The choice of t_1 and t_2 depends on the simulation. For most FDTD simulations, the spatial resolution, Δ_x, is on the order of $\lambda/10$ to $\lambda/100$. For these simulations, t_1 and t_2 can be the last two time steps. For higher resolutions, as t_1 and t_2 become closer in seconds, the values of q_1 and q_2 also become closer and closer, and the roundoff errors become more significant. t_1 and t_2 are taken a few time steps apart (25 was used for this paper) to reduce the roundoff errors. This method provides accuracy similar to the Fourier transform method for both magnitude and phase. An additional source of errors which must be avoided is dc offsets and numerical noise in the time-domain data. Ramped sine excitations known not to cause a dc offset should be used [5]. These excitations have also been shown to reduce numerical noise [6].

This new method provides dramatic savings in computer time and memory over the traditional methods of peak detection or Fourier transformation as shown in Table 1. These savings are obtained because both the peak detection and Fourier transform methods require calculations to be made over the last half-cycle of the simulation, and the two-equation two-unknowns method requires only a single calculation. In addition to the savings from the computation of frequency-domain values, significant savings are also obtained for low-frequency calculations because the simulation does not need to be run for a full cycle past convergence as it must be for peak detection and Fourier transform.

Table 1. Comparison of peak detection, Fourier transform, and the two-equation two-unknowns methods of transforming from time domain to frequency domain methods. The FDTD model is $308 \times 99 \times 67$, cell size is 6 mm, Courant number is 0.5. E_x, E_y, and E_z are converted from time to frequency domain for all cells. Frequency is 10 MHz, number of time steps per cycle is 10,000. The FDTD simulation is run for 10,000 time steps.) Cputime is measured on an HP 755 workstation.

	cpumin	Mwords
FDTD time-domain simulation	2054	18.2
Discrete Fourier Transform	3640	15.1
Peak Detection	2147.1	7.56
Two-equation two-unknowns	2.9	7.56 (disk or RAM)

Millimeter-Resolution Model of the Human Body

In collaboration with Dr. James Lee of the Medical Imaging Laboratory, School of Medicine, and Dr. Mark Nielson of the Department of Biology, University of Utah, a millimeter-resolution model of the human body from the MRI scans of a male volunteer was developed. The resolution is 1.974 mm in the axial plane and 3 mm along the height of the body. The MRI sections were converted into images with defined 30 tissue types whose electrical properties are then specified at the radiation frequency. The tissues are fat, muscle, compact bone and bone marrow, cartilage, skin, brain, nerve, cerebrospinal fluid (CSF) intestine, spleen, pancreas, heart, blood, eye humor, sclera, lens, liver, kidney, lung bladder, stomach, ligament, testicle, spermatic cord, prostate, pineal gland, pituitary gland, and erectile tissue. The pineal gland is suspected of being involved in the bioeffects of power frequency EMFs and has, therefore, been separately identified.

Since it is impossible to run the $1.974 \times 1.974 \times 3$ mm resolution model with the memory sources readily available to us, the voxels were combined to give averaged electrical properties in a $6 \times 6 \times 6$ mm^3 model. Using 5 cells to the second-order Mur absorbing boundaries, and a perfectly conducting ground plane under the feet, the model requires a calculation space of $99 \times 67 \times 308$ (approximately 2 million cells).

Currents and Fields

Current and SAR distributions have previously been calculated using FDTD in 1.31- and 2.62-cm-resolution models of the human body for frequencies from 20 to 915 MHz [1], and for a 1.31-cm-resolution model at 60 Hz [8]. These 60 Hz calculations demonstrated the usefulness of frequency scaling. Because of the quasi-static nature of the coupling to the human body at 60 Hz and 5 or 10 MHz, this method relies on equating the currents entering the human body due to electric and magnetic fields. The FDTD simulation is run at 10 MHz, and the results are scaled to 60 Hz by multiplying the fields by 60 Hz/10 MHz. For the 1.31-cm-resolution model, one period of the sine wave is 4580 time steps. In [8], the simulation was run for two cycles of the wave, and the peak was found using the peak detection algorithm over the last cycle. In the 6-mm-resolution model, one period of the 10 MHz wave has 10,000 time steps. Since this model is quite large, running even two cycles of the wave is prohibitively expensive. Hence, the two-equation two-unknowns method was developed and used.

The FDTD simulation was run for a frontally incident, vertically polarized electric field of 10 kV/m with an assumed magnetic field of 26.53 A/m (33.33 μT) polarized from arm to arm of the model. Total vertical currents in each layer were calculated, and are shown in Fig. 1. These agree with the analysis of Deno [9]. The dashed line gives the total currents passing through the layer, as would be measured with a loop-type measuring device of the experimental method of Deno. As expected, the currents are passing from head to foot except for some upward-directed currents in the arms. The peak current densities in each layer are shown in Fig. 2. The torso regions have peak values above the recommended 10 mA/m^2 limit [10]. To be certain that these peak currents are not a numerical artifact on the external surface of the body, a detailed examination was made of the layers of the peak current. It was found that these peak currents are, indeed, deep within the body. The one exception is the region containing the arms and hands, which hang at rest at the sides of the body. For these layers, the peak current densities are

roughly in the center of the arm and hand, although large currents were also found in the chest region.

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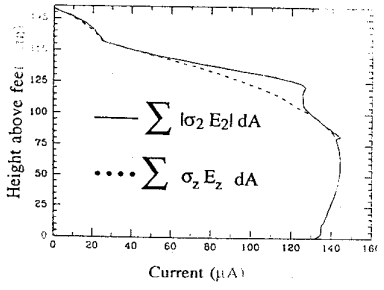

Fig. 1. Total vertical currents passing through the body.

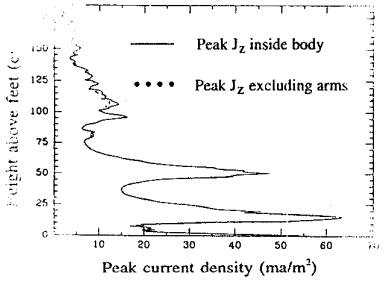

Fig. 2. Peak current density in each layer of the body.