A Simple Convolution Procedure For Calculating Currents Induced in the Human Body For Exposure to Electromagnetic Pulses

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***Abstract*— The finite-difference time-domain (FDTD) and frequency dependent finite difference time-domain $(FD)^2TD$ methods have been previously used to calculate internal electric (E) fields and induced currents for exposure of the anatomically based model of the human body to electromagnetic pulses (EMPs) and continuous wave (CW) sinusoids. The limitation of these methods is that a complete, computer resource intensive, simulation must be done for each different waveform of interest. This paper describes a simple and efficient technique based on convolution theory which provides the response of the body to any incident waveform (EMP or CW) from a single simulation with an incident impulse waveform. This allows the impulse response to be stored, and the response of the body to any desired waveform to be efficiently computed on a small computer or PC.**

I. Introduction

The finite-difference time-domain (FDTD) and frequency-dependent finite-difference time-domain ($(FD)^2TD$) methods have previously been used to calculate internal electric (E) fields and induced currents in a 45,024-cell, 1.31-cm (nominal 1/2") resolution, anatomically based model of the human body exposed to a frontally incident electromagnetic pulse (EMP) prescribed in the time-domain [1], [2]. The limitation of these procedures is that the simulation must be rerun for every EMP waveform of interest. This paper describes a simple method based on convolution theory to obtain the response of the body to any pulse shape based on its response to an impulse EMP. By precalculating and storing this impulse response, the body's response to any other incident waveform (including continuous wave sinusoidal) can be found with minimal computer resources without rerunning the simulation.

II. Anatomically Based Human Model

The model of the human body was developed using sectional diagrams [3] overlaid with a grid. For each of the available cross sections, the predominant tissue type (one of 16 tissue types such as muscle, fat, bone, blood, etc.) was identified for each of the square grid cells of dimensions 0.635×0.635 cm ($1/4'' \times 1/4''$). Interpolating between the anatomical cross sections that were available with variable separations of 2.3–2.7 cm, compositions of the various tissues were then obtained for cubical subvolumes(cells) of dimensions 0.635 cm ($1/4''$) on a side. Since this resulted in a model with about 360,000 cells representing the whole body (about 3 million cells for the entire interaction space, including space between the body and absorbing boundaries), this model was difficult to accommodate in the memory space of readily accessible computers. A model with cubical cells of twice the initial dimension (1.27 cm or $1/2''$) was obtained by combining the data for $2 \times 2 \times 2 = 8$ of the initial cells. Without changes in the anatomy, this process allows some variability in the height and weight of the body. The final cell size of 1.31 cm is used to obtain the total height and weight of 175.54 cm and 69.6 kg, respectively. In some simulations, a 2.62 cm thick layer of dielectric $\varepsilon_r = 4.2$ is added to simulate a human wearing rubber-soled shoes. This model is valid to approximately 725 MHz, where the minimum wavelength in the model is 5.25 cm. The 1.31 cm cell size is $\lambda_{\min}/4$ at this frequency. This minimum wavelength is for muscle tissue. Spleen tissue is very similar to muscle tissue in wavelength, and other tissues have longer wavelengths.

Dispersion of the tissue properties with frequency is neglected in the standard FDTD algorithm, so the properties of the tissues at approximately the midband of the desired EMP are used. For the first example in this paper, the frequency band of this and similar EMPs is approximately 0–100 MHz, so tissue properties at 40 MHz (close to the resonance frequency of the model) were used. The frequency dependent finite-difference time-domain ($(FD)^2TD$) algorithm [2], [4] simulates the dispersion of the tissue properties and is used for the second example in this paper. This algorithm fits a second order Debye equation to the tissue properties ($\varepsilon^*(\omega)$), converts the equation $\mathbf{D} = \varepsilon^*(\omega)\mathbf{E}$ to a second order differential equation in the time domain, and solves this in addition to the standard FDTD equations, which are based on Maxwell's equations. The $(FD)^2TD$ method gives identical results to the FDTD method if the tissues are nondispersive and the second order Debye equation can match the tissue properties over relatively wide bandwidths on the order of 1000–1500 MHz. In a practical $(FD)^2TD$ simulation with frequency dispersive properties a small error is induced because of a slight mismatch between the Debye equation and the measured tissue properties. This error is less than that induced by

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assuming nondispersive tissue properties and using FDTD for a wide-band simulation.

III. Impulse Response

A distinct disadvantage of the standard FDTD and $(FD)^2TD$ methods described in [1], [2] is that a complete simulation requiring the use of a large memory (25–45 Mbytes) mainframe computer or workstation must be run for each individual EMP. This disadvantage can be overcome by computing and storing the impulse response of the body (using a large computer) and convolving it with any desired incident waveform to find the response of the body to the desired waveform (using a small computer).

The impulse response of the body is found by calculating and storing the time domain response of the model to a narrow unit-magnitude flat-top impulse of $5\Delta t = 0.109$ ns. This "impulse" incident field is unity for the first 5 time steps, and zero for all others. Δt is the time step used for the FDTD or $(FD)^2TD$ simulation and is given by the cell size $\Delta = 1.31$ cm divided by $2v_c$, where $v_c = 2.996 \times 10^8$ m/s is the velocity of EM waves in air. For these examples, the time-domain layer-averaged induced current response for several layers in the human model was stored as the impulse response. Similarly, electric or magnetic fields at any or all locations could be stored as the impulse response, if these fields were the quantity of interest. It should be noted the convolution method described below can also be applied as long as the incident field to obtain the "impulse response" is any ultra wide-band pulse containing all the frequencies of interest. The flat-top impulse was chosen because it contains nearly equal energy at all frequencies, i.e. the frequency response is constant over a very broad frequency range.

Since this incident impulse waveform contains energy in a very wide frequency spectrum, frequencies above the 725 MHz limit (based on 1.31 cm cell size) of the human model are included and are therefore not properly modelled in the FDTD simulation. However, this is a linear system, so the improperly modelled frequencies do not interfere with the properly modelled frequencies. Data on frequencies up to the lattice limit will be accurate, and data above the lattice limit can be ignored. In addition, frequencies above the limit of the model are rapidly dispersed by "grid dispersion" in the FDTD lattice [5], so do not appear in the impulse response regardless of the type of scatterer. It is important to be aware of this limit, however, so as not to attempt to obtain accurate results for frequencies above the lattice limit of the model. To analyze higher frequencies, a smaller cell size must be used.

IV. Convolution Integral Method Example 1

The induced-current responses of different layers of the body, $I_i(t)$, to a desired waveform, $E^{\rm des}(t)$, can be found from the induced-current impulse responses, $H_i(t)$, using the following convolution integral

$$I_i(t) = \int_0^T E^{\rm des}(\tau) H_i(t-\tau)\,d\tau \tag{1}$$

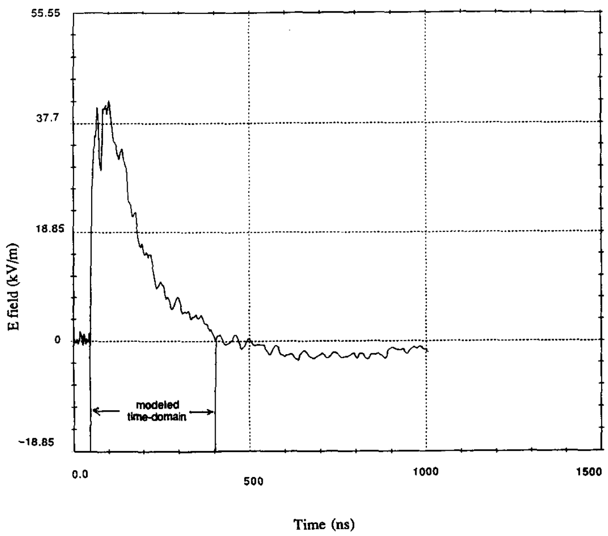

Fig. 1. An Electromagnetic Pulse (EMP) prescribed in the time domain. Because of the rapidly diminishing fields and induced currents, only the first 350 ns of the pulse were modelled. Peak incident field = 41.5 kV/m.

where the integration time T is a period in excess of the time duration of the desired waveform. Since the convolution integrals of (1) are relatively simple and can be carried out with a microcomputer, or even a personal computer (PC), the response of the human body can thus be obtained for any waveform without the need to run the entire human model again and again.

For the EMP given in Fig. 1, the induced currents for the sections through the ankles, knees, thighs, heart and neck were calculated using the convolution integrals of (1). The simulation was run using FDTD with tissue properties taken at 40 MHz, for the human model, with shoes, standing on a ground plane. The impulse response, $H_i(t)$, of the current through the representative section of the ankles (13.76 cm above the feet) is shown in Fig. 2(a). Fig. 2(b) shows the time variation of the currents in the ankle section after performing the convolution integral of (1) compared to those obtained using the EMP of Fig. 1 as the incident field for the detailed man model [1]. There is excellent agreement of the results obtained using the simpler impulse response and convolution method with the results obtained from the exact simulation.

V. Fourier Transform Method Example 2

A method theoretically equivalent to convolution in the time domain (1) is multiplication in the frequency domain. Thus the response of the human body, $I_i(t)$, to a desired incident waveform, $E^{\rm des}(t)$, can be obtained from the "impulse" response, $H_i(t)$, of the body to a broad-band incident waveform, $E^{\rm inc}(t)$ as in

$$I_i(t) = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}\{E^{\rm des}(t)\}\mathcal{F}\{H_i(t)\}}{\mathcal{F}\{E^{\rm inc}(t)\}}\right\} \tag{2}$$

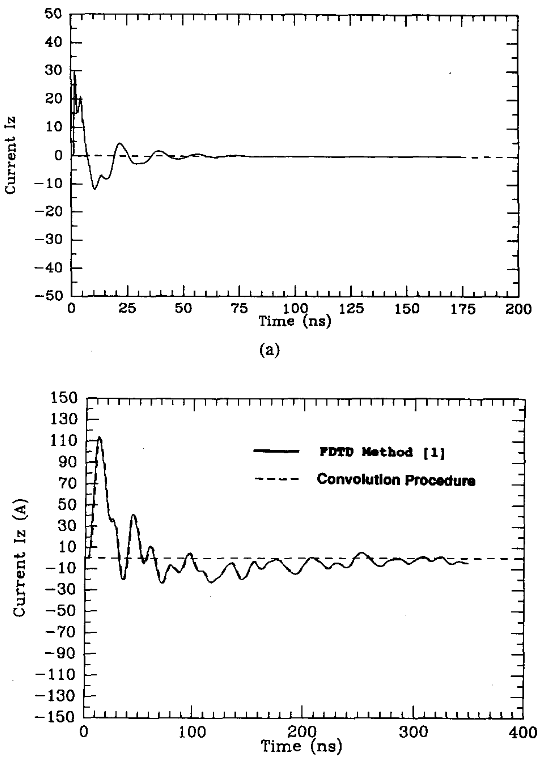

Fig. 2. Currents induced in the section through the ankles (a) Impulse Response (b) Current induced by the EMP of Fig. 1.

where $\mathcal{F}$ represents the discrete fourier transform (DFT) operation, and may be efficiently calculated using the fast fourier transform (FFT) algorithm.

For the broadband EMP (0–800 MHz) given in Fig. 3, the induced currents for the sections through the eyes, neck, heart, liver, bladder, knees and ankles were calculated using (2). The simulation was run using $(FD)^2TD$ for the human model without shoes, in free space, including the effects of frequency dispersion of the tissue properties. The impulse response, $H_i(t)$, of the current through the representative section of the knees (50.4 cm above the feet) is shown in Fig. 4(a). Fig. 4(b) shows the time variation of the currents in the knee section calculated using (2) compared to those obtained using the EMP of Fig. 3 as the incident field for the detailed man model [1]. Again, there is excellent agreement of the results obtained using the simpler impulse response and convolution method with the results obtained from the exact simulation.

This convolution method has also been used to compute the continuous wave (CW) sinusoidal response from a wide-band pulse simulation using the DFT approach (2), with excellent success [6].

A few details are of interest. To obtain correct results, the incident pulse, $E^{inc}(t)$, the desired pulse, $E^{des}(t)$, and the impulse response, $H_i(t)$, must be converged to zero within the length of the Fourier transform or the period of the convolution integral. This is because both (1) and (2) in their discrete form predict a periodic series of these waveforms, even if we choose to analyze only a single period of this series. If the waveforms

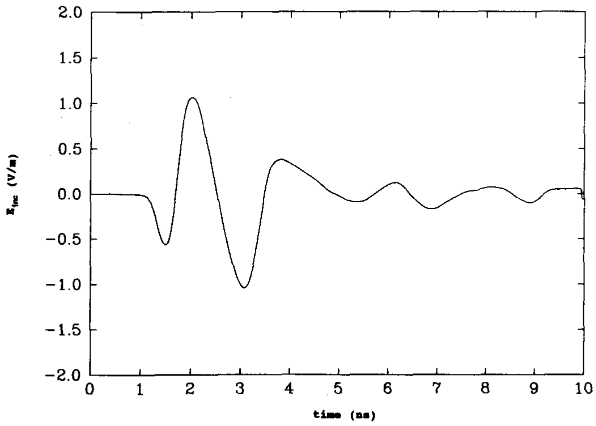

Fig. 3. A broadband Electromagnetic Pulse (EMP) prescribed in the time domain. This pulse was assumed to converge to zero after 10.9 ns. Peak incident field = 1.1 V/m.

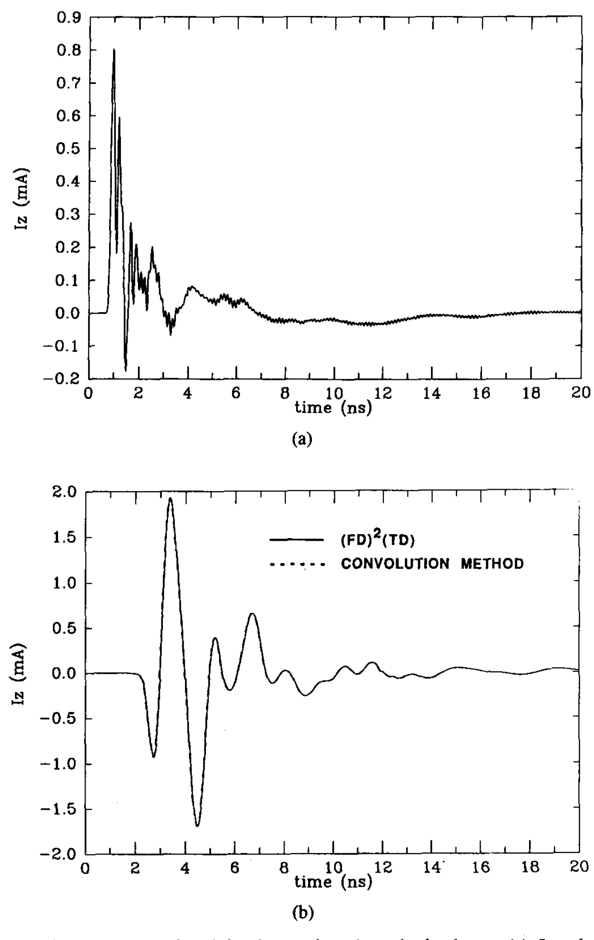

Fig. 4. Currents induced in the section through the knees (a) Impulse Response (b) Current induced by the EMP of Fig. 3.

have not converged to zero, both (1) and (2) will predict that the first time step and the last time step are equal nonzero values, and consequently predict artificial early time transients. To eliminate this problem, a few zeros can be added to the end of the nonzero waveform, and either (1) or (2) can be used to predict the correct waveform. To predict the transient CW response, zeros must be added to end of the desired incident sine wave, $E^{des}(t)$, or it will appear to be a steady state sine wave because of the periodicity, and provide only the steady state response.

VI. Conclusion

This paper describes a simple and efficient technique based on convolution theory which provides the response of the body to any incident waveform (EMP or CW) from a single simulation with an incident impulse waveform. This allows the impulse response to be stored, and the response of the body to any desired waveform to be computed on a small computer or PC. Excellent comparisons with exact simulations are obtained.

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