THE EVALUATION OF SCATTERED ELECTROMAGNETIC WAVES FROM WALKING HUMAN LEGS BY FDTD METHOD

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ABSTRACT
Scattering of the electromagnetic waves from the moving objects are evaluated by using the FDTD method. The moving object is determined as human legs and the severe movement cases are considered. The human legs are modeled by two cylinders and the movement equations for these cylinders are obtained. The circular electric current ring source is chosen as the transmitting antenna. The electromagnetic waves scattered from the human legs are calculated. The incident wave equations and the movement equations for surface of the object are transformed to the discrete forms and the results and graphics of the scattered field are obtained for three different movement models, which are described seperately. Both the uniqueness of the solution and the criteria that cell dimensions should obey are provided and the Courant stability condition is taken into account in the determination of the time steps.

I. INTRODUCTION
For the security purpose, for example (a) observation of the entrances and exists to the wharehouses without human control; (b) observation of the suspicious behaviours of the ones having terroristic aims at the airports in the regions out of sight, by radio waves and/or microwaves, the solutions of the electromagnetic waves scattered from the moving objects are necessary. The device, which may be used for this problem should analyse the movement of the human first and should decide whether the characteristic structure of the movement is suspicious or not. Second, the realization of such a device can be possible if the solution of the direct scattering problem is known. So, suitable expressions of the electromagnetic wave scattered from the walking human or other objects moving like human in a bounded region of are obtained in time domain.

In this paper, firstly a model for the human walking in cylindrical coordinates is developed. Human legs are chosen as the moving object and they are modeled with two cylinders varying in time domain. The equations for this model are obtained and then the problem space and appropriate sizes are determined. Outer radiation boundary conditions are constructed and the cell dimensions and time step are calculated. The effective dielectric constant and conductivity values of the leg are calculated for 100 MHz by using debye constant from Furse's work [1, 2]. The three dimensional mixture model of the object is obtained [1], [3-5]. A computer program is prepared to determine the scattered field. The numerical results are obtained for the scattered electric and magnetic field in problem space for three different movement models by using this computer program. The results are given in graphics.

II. FORMULATION OF THE PROBLEM
In this section walking processes of human movement are modeled.

MODELING OF THE WALKING HUMAN LEGS

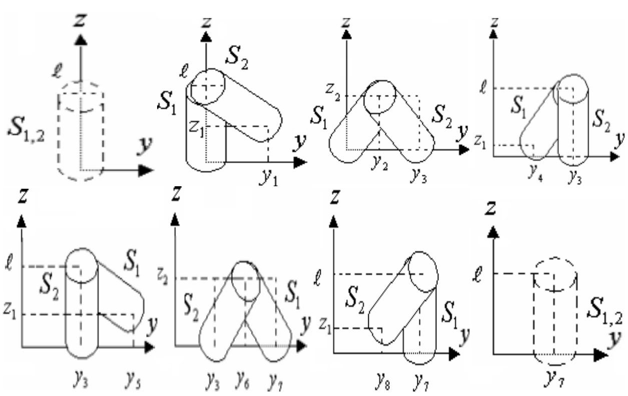


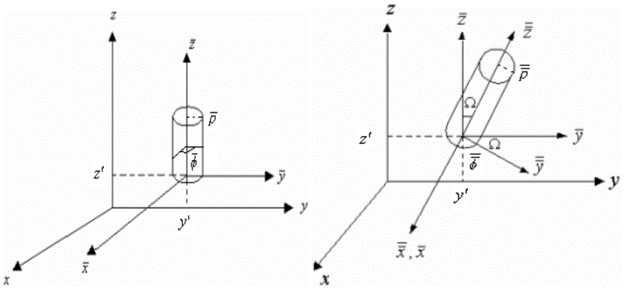
Figure 1. Human legs model at the $t = t_0 + 0$, $t = t_1$, $t = t_2$, $t = t_3$, $t = t_4$, $t = t_5$, $t = t_6$, $t = t_7$ and $t = t_8 - 0$ instants.

Various phases of walking process are depicted in Figure 1, where $t_0 < t_1 < t_2 < t_3 < t_4 < t_5 < t_6 < t_7 < t_8$, in which the intervals $(t_0, t_1]$,....,$[t_7, t_8)$ defines the specific phases of walking process. For example, the situation in the $t \in (t_4, t_5]$ time interval is obtained by the expressions of the S_1 and S_2 cylinder surfaces below:

$$S_1 \equiv \left\{ (\rho, \phi, z) \middle| \overline{\overline{\rho}}(\rho, \phi, t) = a, \ \ V_z(t - t_4) < z < l, \ \ \overline{\overline{\phi}} \in [0, 2\pi) \right\} \quad (1)$$

$$S_2 \equiv \left\{ (\rho, \phi, z) \middle| \overline{\rho}(\rho, \phi) = a, \ \ 0 < z < l, \overline{\phi} \in [0, 2\pi) \right\} \quad (2)$$

Here $\overline{\overline{\rho}}$, $\overline{\overline{\phi}}$, $\overline{\rho}$ and $\overline{\phi}$ are shown in Figure 2.



(a) (b)

Figure 2. Coordinate systems (a) shifted (b) rotated.

MOVEMENT MODELS

In this section, the definition of the three different movement models are given. Models are prepared by assuming the movement of the human as being in normal, anxious, and/or suspicious state and these movements are named as "normal movement", "anxious movement" and "suspicious movement".

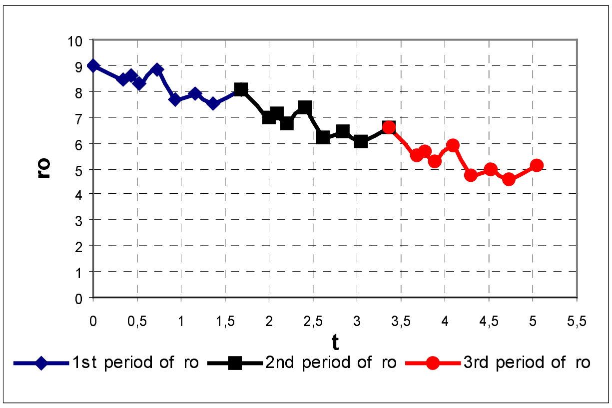


Figure 3. The variation of the position of radius of object for the "normal movement" for three periods.

In the movement model named as "normal movement" three assumptions are done: 1) at the t=0 instant the cylinders modeling the human legs are over outer radiation boundary surface, 2) human legs started walking with initial speeds V_z, V_ρ, V_{az}, V_{kz}, $V_{a\rho}$, $V_{k\rho}$ at the plane $\phi = \pi/2$, and 3) speeds of the human legs during three periods remained constant. The variation of this movement is depicted in Figure 3 in time domain. Variation of the position of radius of object for "normal movement" in time domain is illustrated for all three periods in Figure 3.

In the movement model named as "anxious movement" the cylinders modeling human legs are assumed to be over outer radiation boundary surface moving with the constant speeds of V_z, V_ρ, V_{az}, V_{kz}, $V_{a\rho}$, $V_{k\rho}$ at the $\phi = \pi/2$ constant plane at t=0 instant of the first period. In the second period, the speeds remain constant, but with the half of first period and at the third period having the same speed with the first period is assumed. The time variation of this movement is given in Figure 4. The variation of the position of radius of object for "anxious movement" is given in Figure 4 for three periods.

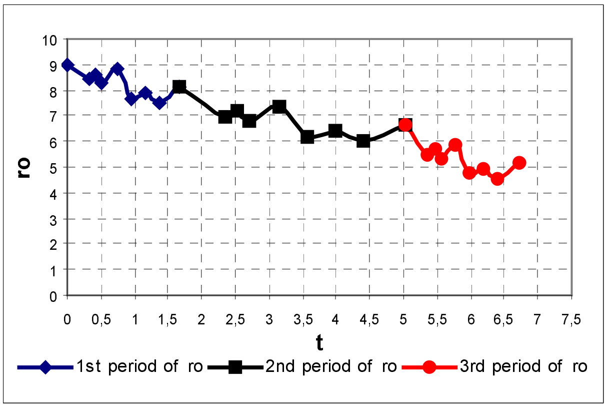


Figure 4. The variation of the position of radius of object for the "anxious movement" for three periods.

In the movement model named as "suspicious movement", in the first period at t=0 instant the cylinders modeling human legs are assumed to be over outer radiation boundary surface moving with the constant speeds of V_z, V_ρ, V_{az}, V_{kz}, $V_{a\rho}$, $V_{k\rho}$ at the plane of $\phi = \pi/2$.

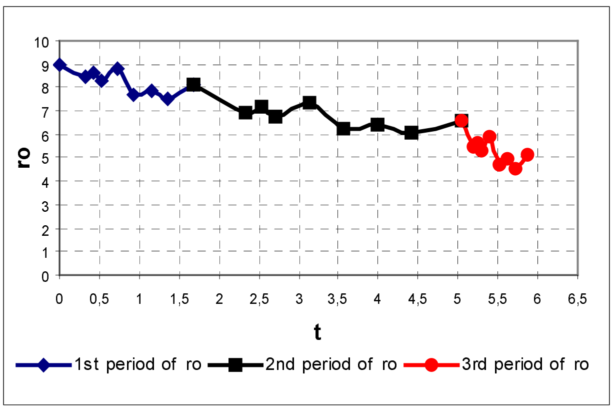


Figure 5. The variation of the position of radius of object for the "suspicious movement" for three periods.

In the second period, the speeds are half of the first period and constant. Also in the third period the speeds remain constant but four times of the velocity in the second period and two times of the velocity in the first period. The variation of this movement in time domain is given in Figure 5. The variation of the position of radius of object for the "suspicious movement" for three periods is shown in Figure 5.

PROBLEM SPACE

An electric current ring with radius a on $z=h$ plane centered at the point Q(0, 0, h) is chosen as the transmitter antenna. The magnetic vector potential at a point P, which is at distance R from the antenna turns to form below [6]:

$$\tilde{A} = aC^{-1/2}e^{ik\sqrt{C}}\int_{\bar{\phi}}^{2\pi}(\cos\bar{\phi}\;\; d\bar{\phi}\;\; \vec{e}_x + \sin\bar{\phi}\;\; d\bar{\phi}\vec{e}_y) \quad (3)$$

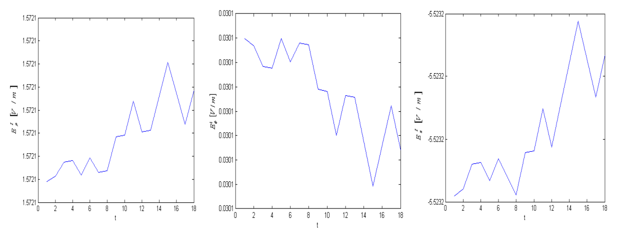
$$C = \left(\rho\sin\phi - a\sin\bar{\phi}\right)^2 + \left(\rho\cos\phi - a\cos\bar{\phi}\right)^2 + \left(z - \bar{z}\right)^2 \quad (4)$$

The result of the value $\bar{\phi}$ in equation (3) is increased at the interval [0,2π) by $\Delta\bar{\phi}$ and the value of the integral at this point is multiplied by $\Delta\bar{\phi}$. The numerical results are obtained by adding these results. Electric and magnetic field expressions are calculated numerically by using the magnetic vector potential. Components of magnetic vector potential in circular cylindrical coordinate system are calculated by using the equations below:

$$\tilde{A}_\rho = \tilde{A}_x \cos\phi + \tilde{A}_y \sin\phi \quad (6)$$

$$\tilde{A}_\phi = -\tilde{A}_x \sin\phi + \tilde{A}_y \cos\phi \quad (7)$$

The specification of the problem space is possible with the specification of outer radiation boundary surface first. The graphics of the incident electric field at observation point P($6, \pi/2,\ 2$) is given in Figure 6.



(a) (b) (c)

Figure 6. The variations of components (a) E_ρ^i, (b) E_ϕ^i, (c) E_z^i in time domain at observation point P($6, \pi/2,\ 2$).

The time step of the three dimensional circular cylindrical region is determined by Courant stability criteria as:

$$v\Delta t \le \left[\left[(\Delta\rho)^{-2}\right] + \left[\left(\rho\;\Delta\phi\right)^{-2}\right] + \left[(\Delta z)^{-2}\right]\right]^{-1/2} \quad (7)$$

We obtain $\Delta t \le 3.51.10^{-10}$ s when the cell dimensions of the inner smallest cell is used in (7).

For detection of the moving object in problem space along $5-10$ s, remaining between time step 1.75×10^{12} and 2.62×10^{12} should be used. When the relations of the field components to ρ, ϕ, z, t are thought, the evaluation of the scattered field components are nearly impossible to calculate with computers in use. $\partial\vec{D}/\partial t$ is calculated as 10^{-10} by using the variation of displacement vector in time as so small and by choosing the time step as 3×10^{-10} s. So, variation of the displacement vector may be neglected and $\partial\vec{D}/\partial t$ may be assumed as zero in this work. Under these conditions, the necessity of using Courant stability criteria vanishes and Δt is chosen as 0.3 s which makes the detection of the movement possible.

THREE DIMENSIONAL MIXTURE MODEL

The cylindrically shaped cell used in this model may be consisted more than one tissue because of its sizes. The need of the dielectric constant and conductivity being constants in a cell makes the calculation of an effective dielectric constant and effective conductivity necessary. In such mixture models, two criteria should be taken into account.

The first is a formula known as the Bruggeman formula, which is also commonly named as Polder - Van Santen formula in remote sensing applications:

$$(1-f)\frac{\varepsilon_e - \varepsilon_{eff}}{\varepsilon_e + 2\varepsilon_{eff}} + f\frac{\varepsilon_i - \varepsilon_{eff}}{\varepsilon_i + 2\varepsilon_{eff}} = 0 \quad (8)$$

The volume ratios used in this formula are given in Table 1.

Table 1. Volume ratios of the tissues used in human leg model and $\varepsilon_i, \varepsilon_e, \sigma_i, \sigma_e$ values.

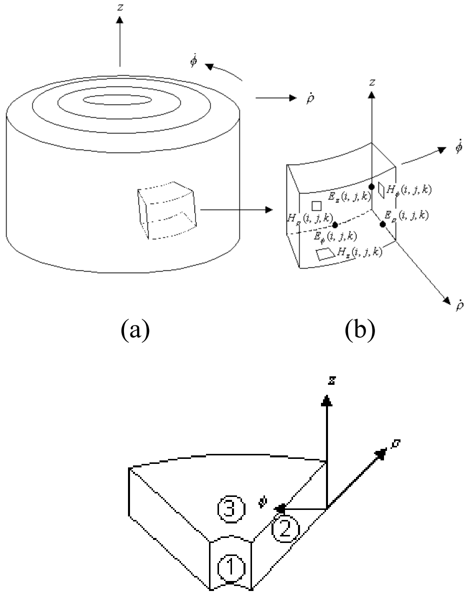
Tissue	f	1-f	ε_i	σ_i	ε_e	σ_e
bone	0.4225	-	7.4639	0.0603	-	-
muscle	-	0.5775	-	-	63.65	0.7523
bone+muscle	0.9047	-	31.883	0.3489	-	-
fat	-	0.0953	-	-	7.4639	0.0603
Bone+muscle+fat	0.9721	-	28.8031	0.3113	-	-
skin	-	0.0279	-	-	59.4776	0.6549

The volume ratios are obtained from an empirical work which uses the surface thickness of the tissues [1]. Table 2, consists the effective dielectric constant and conductivity values, which are calculated using this work.

Table 2. The effective dielectric constant and conductivity values of the human legs model.

Region	ε_r	$\sigma(S/m)$
leg	29.4445	0.3184

DISCRETE FIELD FORMULATION



(a) (b)

(c)

Figure 7. (a) Problem space; (b) FDTD cell of this space; (c) Boundary surfaces.

The boundary surfaces, which the boundary conditions relate in equations (9-12) is given in Figure 7.c. For example for the boundary surface 1, valid boundary conditions are given below:

$$E_\phi^{s,n+1/2}(I,J,K) = E_\phi^{s,n+1/2}(I-1,J,K) + Q^{n+1/2}(I-1,J,K)\ E_\phi^{i,n+1/2}(I-1,J,K) \quad (9)$$

$$E_z^{s,n+1/2}(I,J,K) = E_z^{s,n+1/2}(I-1,J,K) + Q^{n+1/2}(I-1,J,K)\ E_z^{i,n+1/2}(I-1,J,K) \quad (10)$$

$$H_\phi^{s,n+1}(I,J,K) = H_\phi^{s,n+1}(I-1,J,K) + Q^{n+1}(I-1,J,K)\ H_\phi^{i,n+1}(I-1,J,K) \quad (11)$$

$$H_z^{s,n+1}(I,J,K) = H_z^{s,n+1}(I-1,J,K) + Q^{n+1}(I-1,J,K)\ H_z^{i,n+1}(I-1,J,K) \quad (12)$$

From the boundary conditions defined above, the appropriate one according to the boundary surface or surfaces are chosen and the total field in scatterer is calculated. Q, is a suitable object function equal to 1 if there is electric field coming from antenna directly, else is equal to zero.

II. CONVERSION OF SCATTERED FIELD EXPRESSIONS INTO DISCRETE FORM

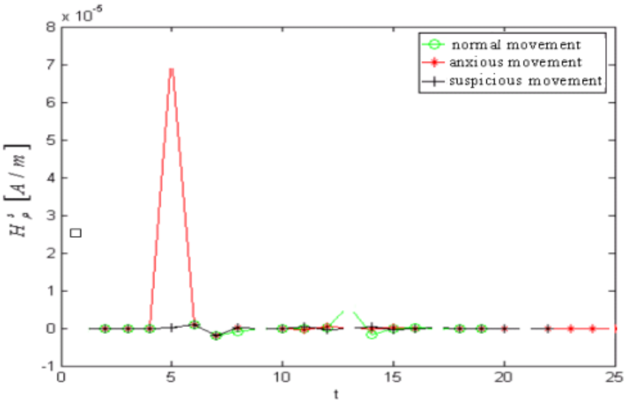
When finite difference forms are substituted in the scattered field expressions, six equations giving the scattered field in discrete form are obtained. One of these equations is given below:

$$\left(\frac{\varepsilon^{n+1/2}(I,J,K)}{\Delta t} + \sigma^{n+1/2}(I,J,K)\right) E_\rho^{s,n+1/2}(I,J,K) - \frac{H_z^{s,n+1}(I,J,K)}{\rho(J)\ \Delta\phi} + \frac{H_\phi^{s,n+1}(I,J,K)}{\Delta z} = \frac{\varepsilon^{n-1/2}(I,J,K)}{\Delta t} E_\rho^{s,n-1/2}(I,J,K) - \frac{H_z^{s,n+1}(I,J-1,K)}{\rho(J)\ \Delta\phi} + \frac{H_\phi^{s,n+1}(I,J,K-1)}{\Delta z} + \frac{\left(\varepsilon^{n-1/2}(I,J,K) - \varepsilon_0\right)}{\Delta t} Q^{n-1/2}(I,J,K) E_\rho^{i,n-1/2}(I,J,K) - \sigma^{n+1/2}(I,J,K)\ Q^{n+1/2}(I,J,K) E_\rho^{i,n+1/2}(I,J,K) \quad (13)$$

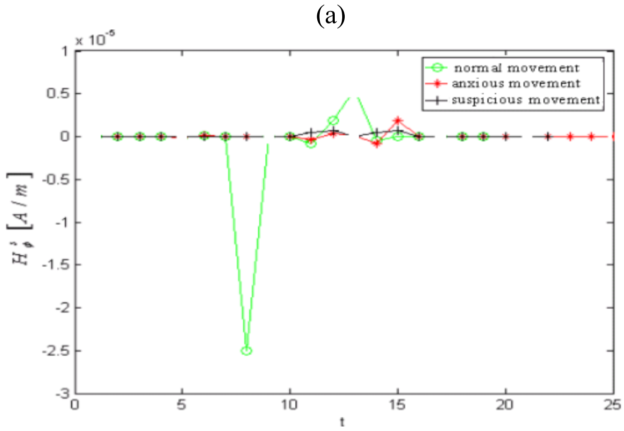
III.SOLUTIONS AND CONCLUSIONS

By using the computer program prepared for the determination of the scattered field in problem space, numeric results and graphics of the electric and the magnetic field scattered from the object moving with constant velocity and with varying velocity are obtained and interpretations about these graphics are given. The legs are modeled with a cylinder having the height 1 m and radius 10 cm. The legs are assumed to be on the outer radiation boundary surface at the instant t=0 and afterwards moving with V_ρ = 1.727 m/s in the direction ρ at the plane $\phi = \pi/2$. In this problem, outer radiation boundary surface, cylindrical lateral surfaces of ρ = 4 m and ρ = 9 m, and planes of z = 0 and z = 5.6 m are chosen to provide the specifications of cell dimensions should be between 0,15 m and 0,3 m. On the surface of ρ=4 m $E^T \approx E^i(\rho,\ \phi,\ z)$ is assumed. The other boundary surfaces are covered with an absorber. The time interval is chosen as 0,3 s in the graphics giving the variation of the field.

Three different simulation models are given here. In the first model, the movement of the object have normal behaviour. The objects have anxious and suspicious behaviours in the second and third model, respectively. These three models are called “normal movement”, “anxious movement” and “suspicious movement”. The movement of the object is analyzed for three different period durations. By using the computer program prepared for the determination of the scattered field in problem space, numeric results and graphics of the electric and the magnetic field expressions of the object moving with constant velocity and with varying velocity are obtained and interpretations about these graphics are given.



(a)



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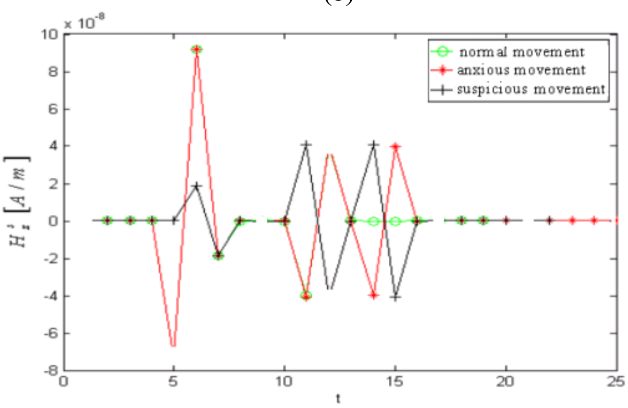

(c)

Figure 8. The variation of (a) H_ρ^s, (b) H_ϕ^s and (c) H_z^s with time at the observation point $P(6, \pi/2, 2)$.

In Figure 8.a, the variation of the component ρ of the scattered magnetic field with time at the observation point $P(6, \pi/2, 2)$ for “normal movement”, “anxious movement” and “suspicious movement” is given. Figure 8.b and Figure 8.c are the variations of the components ϕ and z of the scattered magnetic field with time at the observation point $P(6, \pi/2, 2)$ for “normal movement”, “anxious movement”, and “suspicious movement”, respectively.

IV. RESULTS

In this work, moving object model in a form similar to the walking human is composed in cylindrical coordinate system. Human legs are chosen to be the moving object and is modeled with two finite cylinders. The expressions for the movement of this object is obtained. FDTD method is used for the solution of the direct scattering problem.

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