SURFACE INTEGRAL EQUATION MODELING APPROACH TO THE HANDSET ANTENNA AND HUMAN BODY INTERACTION

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***Abstract*— Numerical analysis of the handset antenna and human body interaction in the 900 MHz and 1900 MHz frequency bands based on a surface integral equation (SIE) technique in frequency domain is presented. Simplified models of a head and a hand are used, that can provide satisfactorily accurate results for many applications. All the boundary surfaces are modeled by bilinear quadrilateral surface elements, and the equivalent electric and magnetic surface current density vectors over the elements are approximated by high-order polynomial basis functions in local parametric coordinates. The unknown current-distribution coefficients are determined by a Gelerkin-type method of moments. The SIE modeling theoretical results, obtained on a modest PC in very reasonable amounts of time, are compared to both the experimental results and the theoretical results obtained by a finite-difference time-domain (FDTD) technique from the literature, and a good agreement is observed. The principal aim of this paper, that appears to offer the first SIE-based numerical modeling of an antenna-user interaction, is to promote the SIE method of moments as a general approach to the electromagnetic analysis of a class of biological systems and a useful alternative to the FDTD method in some biological applications.**

I. INTRODUCTION

Hundreds of papers have been published, many of them in the MTT-S journals and symposia digests, on the numerical analysis of electromagnetic systems which include antennas and biological tissues. In all of them, as far as the author of this paper is informed, biological tissues are modeled by using either volume integral equation (VIE) frequency-domain techniques [1,2] or finite-difference time-domain (FDTD) techniques [3,4]. This paper is aimed to present, for the first time, the analysis of one such electromagnetic system by means of a surface integral equation (SIE) frequency-domain technique, as well as to introduce and promote the SIE method of moments, in all its possible future varieties and modalities, as a novel approach in the electromagnetic analysis of biological systems. Based on the results presented in this paper, the author believes that this approach should be regarded as a useful alternative to the FDTD approach in some biological applications.

The system considered consists of a hand-held mobile telephone and a human head model, and the analysis is performed in the 900 MHz and 1900 MHz frequency bands. The telephone is approximated by a purely metallic box, the sides of which are 15 cm, 6 cm, and 2.5 cm long, with a quarter-wave wire monopole antenna attached at the center of the box [4]. The head is approximated by a sphere with a radius of 9 cm. The hand model is also of a rectangular shape, is 10 cm wide and 2 cm thick, and is wrapped around the lower part of the telephone, as shown in Fig.1. Both the head and the hand are modeled as pure muscle of relative permittivity $\epsilon_r = 50.5$ and conductivity $\sigma = 1.2$ S/m at 900 MHz, and $\epsilon_r = 49$ and $\sigma = 1.6$ S/m at 1900 MHz [4]. It is shown in [4] that such a simplified model can provide satisfactorily accurate results for the antenna impedance and radiation patterns, as well as for the antenna radiation efficiency, overall absorbed power, and overall specific absorption rate (SAR). The model in Fig.1 can be used also for obtaining a rough SAR distribution inside the head. It is demonstrated in this present paper that this model can be simulated very quickly on even a modest PC if a well designed and optimized SIE method of moments is used as a solution procedure. This analysis approach may be quite useful for antenna engineers and designers in industry, where effects on the antenna of a person using the telephone, as well as the SAR issues, usually have to be taken into account quickly with an engineering level of precision. Of course, more realistic SIE head models are possible at the expense of the computer memory and computation time.

II. NUMERICAL MODEL

We model the sphere surface by $N_{d1} = 96$ bilinear quadrilaterals, as shown in Fig.1. A bilinear quadrilateral is a very flexible simple parametric surface element [5]. It is defined uniquely by its four vertices, that can be positioned arbitrarily in space. The quadrilateral can be

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described analytically by a bilinear equation of two local parametric (generally non-orthogonal) coordinates, u and v. Its edges and all parametric coordinate lines (defined by $u =$const or $v =$const) are straight, but its surface, a bilinear surface, is generally curved (inflexed). The boundary surface between the hand and air is modeled by $N_{d2} = 14$ bilinear quadrilateral surface elements (Fig.1). The part of the boundary surface of the telephone box which is in contact with air is modeled by means of $N_{c1} = 16$ bilinear quadrilaterals, and the rest of it, which is in contact with the hand, by $N_{c2} = 4$ quadrilaterals. Finally, the wire antenna is modeled as a single wire segment.

According to the surface equivalence principle (generalized Huygens' principle), the electric field vector inside the head can be expressed as

$$\boldsymbol{E}_{\text{in head}} = \sum_{i=1}^{N_{d1}} \boldsymbol{E}(\boldsymbol{J}_i, \boldsymbol{M}_i, \epsilon_r\epsilon_0, \sigma, \mu_0) \ , \qquad (1)$$

where $\boldsymbol{J}_i$ and $\boldsymbol{M}_i$ are the equivalent electric and magnetic surface current density vectors, respectively, over the ith bilinear surface element, S_i. Similarly,

$$\boldsymbol{E}_{\text{in hand}} = \sum_{j=1}^{N_{d2}} \boldsymbol{E}(\boldsymbol{J}_j, \boldsymbol{M}_j, \epsilon_r\epsilon_0, \sigma, \mu_0) + \sum_{k=1}^{N_{c2}} \boldsymbol{E}(\boldsymbol{J}_k, 0, \epsilon_r\epsilon_0, \sigma, \mu_0) \ , \qquad (2)$$

$$\begin{aligned}\boldsymbol{E}_{\text{in air}} = & \sum_{i=1}^{N_{d1}} \boldsymbol{E}(-\boldsymbol{J}_i, -\boldsymbol{M}_i, \epsilon_0, 0, \mu_0) \\ & + \sum_{j=1}^{N_{d2}} \boldsymbol{E}(-\boldsymbol{J}_j, -\boldsymbol{M}_j, \epsilon_r\epsilon_0, \sigma, \mu_0) \\ & + \sum_{n=1}^{N_{c1}} \boldsymbol{E}(\boldsymbol{J}_n, 0, \epsilon_0, 0, \mu_0) \\ & + \boldsymbol{E}(\boldsymbol{J}_{\text{wire-segment}}, 0, \epsilon_0, 0, \mu_0) \ , \end{aligned} \qquad (3)$$

with analogous expressions for the magnetic field vector, $\boldsymbol{H}$. Here,

$$\boldsymbol{E}(\boldsymbol{J}_i, \boldsymbol{M}_i, \epsilon, \sigma, \mu) = -\mathrm{j}\omega\boldsymbol{A}_i - \nabla\Phi_i - \frac{1}{\epsilon}\nabla \times \boldsymbol{F}_i \ , \qquad (4)$$

$$\boldsymbol{H}(\boldsymbol{J}_i, \boldsymbol{M}_i, \epsilon, \sigma, \mu) = -\mathrm{j}\omega\boldsymbol{F}_i - \nabla U_i + \frac{1}{\mu}\nabla \times \boldsymbol{A}_i \ , \qquad (5)$$

$$\boldsymbol{A}_i = \mu \int_{S_i} \boldsymbol{J}_i G \, \mathrm{d}S \ , \qquad (6)$$

$$\boldsymbol{F}_i = \epsilon \int_{S_i} \boldsymbol{M}_i G \, \mathrm{d}S \ , \qquad (7)$$

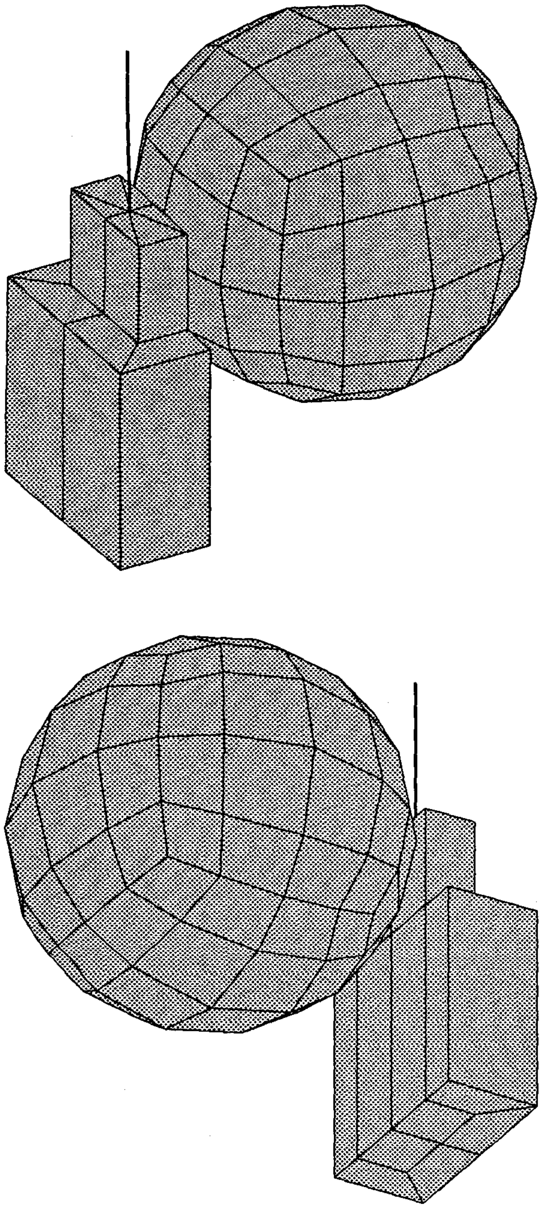

Fig. 1. The handset antenna/human body model used for the surface integral equation (SIE) simulations: two views of the structure. The telephone is approximated by a purely metallic box with a quarter-wave monopole antenna attached at the center of the box, and a spherical model of the human head is adopted. Both the head and the hand are modeled as pure muscle. The model is constructed from a total of 130 bilinear quadrilateral surface elements and one wire segment. For details and dimensions please see the text.

$$\Phi_i = \frac{\mathrm{j}}{\omega\epsilon}\int_{S_i} \nabla_s \cdot \boldsymbol{J}_i G \,\mathrm{d}S\,, \tag{8}$$

$$U_i = \frac{\mathrm{j}}{\omega\mu}\int_{S_i} \nabla_s \cdot \boldsymbol{M}_i G \,\mathrm{d}S\,. \tag{9}$$

$\boldsymbol{A}$ and $\boldsymbol{F}$ are the magnetic and electric vector potential, while Φ and U are the electric and magnetic scalar potential, respectively. G is the Green's function for the unbounded homogeneous medium of parameters ϵ, σ, and μ,

$$G = \frac{\mathrm{e}^{-\gamma R}}{4\pi R}\,, \qquad \gamma = \mathrm{j}\omega\sqrt{\left(\epsilon - \mathrm{j}\frac{\sigma}{\omega}\right)\mu}\,, \tag{10}$$

γ being the propagation coefficient in the medium and R the distance of the field point from the source point.

We approximate the current density vectors over the ith bilinear quadrilateral surface element by the following 2D expansions in the coordinates u and v:

$$\boldsymbol{J}_i = \sum_{m=1}^{N_i} a_{im}\boldsymbol{p}_{im}(u,v)\,; \quad \boldsymbol{M}_i = \sum_{m=1}^{N_i} b_{im}\boldsymbol{p}_{im}(u,v)\,,$$

$$u_1 \le u \le u_2\,, \quad v_1 \le v \le v_2\,; \tag{11}$$

where $\boldsymbol{p}_{im}(u,v)$ are polynomial vector basis functions which satisfy automatically the current-continuity boundary condition along an edge shared by (metallic and dielectric) bilinear surfaces, a_{im} and b_{im} are unknown complex coefficients to be determined, and N_i is the adopted number of basis functions on S_i. Polynomial degrees can be high (high-order current-approximation), enabling electrically relatively large surface elements-domains (large-domain or entire-domain method of moments [5-8]).

The boundary conditions for the tangential components of the electric and magnetic field vectors on the boundary surfaces yield

$$(\boldsymbol{E}_{\text{in head}})_{\text{tang}} = (\boldsymbol{E}_{\text{in air}})_{\text{tang}}\,,$$

$$(\boldsymbol{H}_{\text{in head}})_{\text{tang}} = (\boldsymbol{H}_{\text{in air}})_{\text{tang}} \quad \text{(on surface head-air)}\,; \tag{12}$$

$$(\boldsymbol{E}_{\text{in hand}})_{\text{tang}} = (\boldsymbol{E}_{\text{in air}})_{\text{tang}}\,,$$

$$(\boldsymbol{H}_{\text{in hand}})_{\text{tang}} = (\boldsymbol{H}_{\text{in air}})_{\text{tang}} \quad \text{(on surface hand-air)}\,; \tag{13}$$

$$(\boldsymbol{E}_{\text{in air}})_{\text{tang}} = 0 \quad \text{(on surface metal-air)}\,; \tag{14}$$

$$(\boldsymbol{E}_{\text{in hand}})_{\text{tang}} = 0 \quad \text{(on surface metal-hand)}\,. \tag{15}$$

Having in mind the integral expressions for the fields in Eqs.(1)–(10), the equations (12)–(15) represent a set of coupled electric/magnetic field surface integral equations (SIE) for $\boldsymbol{J}$ and $\boldsymbol{M}$ as unknowns.

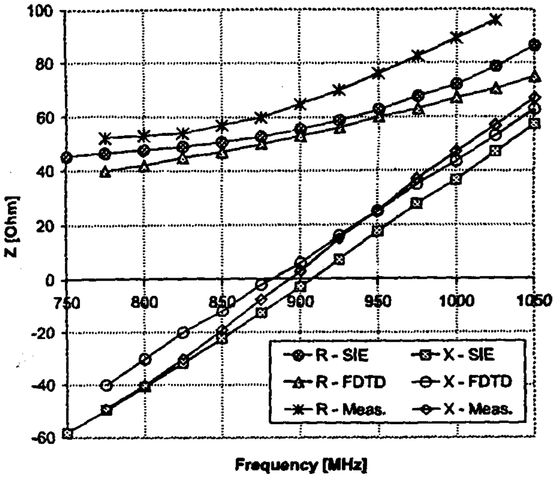

Fig. 2. Impedance of the handset antenna in Fig.1 in a frequency range 750 – 1050 MHz. The theoretical results obtained by the surface integral equation (SIE) method are compared to the theoretical results obtained by the FDTD method (for the same simplified antenna/body system) [4] and to the experimental results (for a real person) [4].

The current-distribution coefficients $\{a\}$ and $\{b\}$ in Eq.(11) are determined by means of the Galerkin testing procedure. Galerkin integrals associated with the head and hand contain Green's function, G, defined in Eq.(10), for the dielectric medium with pronounced losses ($\sigma = 1.2 \div 1.6$ S/m), and the particular attention must be paid to numerical integration of these integrals.

By post-processing of the current-distribution coefficients, we can directly obtain all the quantities of interest, such as the current distributions [Eq.(11)], antenna impedance, field and SAR distribution inside the head [Eq.(1)], and radiation patterns [Eq.(3)].

III. Results

Fig.2 shows the impedance of the telephone antenna in the presence of the operator in a frequency range 750 – 1050 MHz. The results obtained by the surface integral equation method are compared to both the experimental results and the FDTD simulated results reported in [4]. The FDTD simulations were done with the same model shown in Fig.1, while the measurements were performed with a real person holding the metal box. We observe a good agreement between our results and the two sets of results reported in [4]. The total number of unknowns for the approximation of currents in the SIE simulation with using symmetry is 258 at the central frequency, and the corresponding CPU

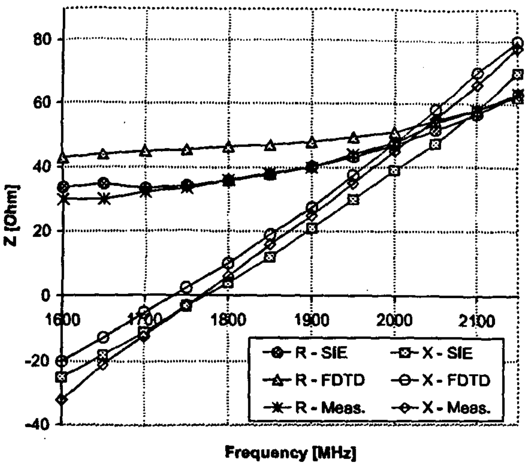

Fig. 3. Impedance of the handset antenna in Fig.1 in a frequency range 1600 – 2150 MHz. The theoretical results obtained by the surface integral equation (SIE) method are compared to the theoretical results obtained by the FDTD method (for the same simplified antenna/body system) [4] and to the experimental results (for a real person) [4].

time required for the analysis 82 seconds on a modest PC (Pentium 166 MHz with 16 MB RAM memory). The total number of cells in the FDTD simulation was 141,680, and the total CPU time 5,296 seconds with a SUN SPARC-2 [4].

Shown in Fig.3 is the impedance of the telephone antenna in Fig.1 in a frequency range 1600 – 2150 MHz. We again observe a good agreement between our SIE-simulation results, which required 752 unknowns with using symmetry and 263 seconds of CPU time at the central frequency with a PC Pentium 166 MHz, and the FDTD-simulation (for the same model) and experimental results (for a real person) reported in [4].

IV. CONCLUSIONS

This paper presents a numerical analysis of the handset antenna and human body interaction in the 900 MHz and 1900 MHz frequency bands based on a surface integral equation (SIE) technique in frequency domain. The telephone is approximated by a purely metallic box with a wire monopole antenna attached at the center of the box, and a spherical model of the human head is adopted. Both the head and the hand are modeled as pure muscle. All the boundary surfaces are modeled by a total of 130 bilinear quadrilateral surface elements, and the equivalent electric and magnetic surface current density vectors over the elements are approximated by high-order polynomial basis functions with a total of a few hundred unknowns, depending on frequency. The CPU time with a modest PC is on the order of several minutes. Our theoretical results are in a good agreement with the theoretical results from the literature obtained by applying the FDTD technique on the same simplified handset antenna/human body model, as well as with the experimental results from the literature obtained by measurements on a system with a real person.

To the best knowledge of the author, the present paper presents the first SIE-based numerical modeling of an antenna-user interaction. Based on the presented results, the author believes that the SIE approach should be regarded as a useful alternative to the FDTD and VIE (volume integral equation) approaches in some biological applications.

V. REFERENCES

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