Evaluation of Electromagnetic Phenomena Induced by Transcranial Magnetic Stimulation

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***Abstract*—The electric current densities induced inside a human head by transcranial magnetic stimulations are evaluated through a Boundary Element model. The results of the computational procedure are first validated by comparison with the ones provided by a commercial finite element code on a test problem. The BEM technique is then applied to a heterogeneous human head phantom radiated by a butterfly coil for transcranial magnetic stimulation.**

***Index Terms*—Boundary element methods, Magnetic field effects, Medical treatment, Modeling, Transcranial magnetic stimulation (TMS).**

I. Introduction

Transcranial magnetic stimulation (TMS) was introduced as a non-invasive neurodiagnostic tool almost thirty years ago. This technique is substantially free of pain and, despite being established as a diagnostic instrument, it is also proved to be a valid therapeutic technique. TMS was originally utilized in clinical neurophysiology for the evaluation of the functional status of the corticospinal tract, involving a single magnetic sinusoidal pulse with a duration of some hundreds of milliseconds [1]. Some years later, a delivery of trains of repetitive magnetic pulses in rapid sequence, with a frequency up to 100 Hz, was introduced as repetitive TMS (rTMS) [2]. It was shown that rTMS interacts with the cortical activity more effectively than the single-pulse TMS. The rTMS allows a modulation of the transient neural excitability with an effect which depends on the frequency of stimulation [3]. This technique has gained therapeutic interest for disorders such as Parkinson's and, more recently, for the treatment of depression [4]. Some promising findings can envisage applications for psychiatric disorders such as schizophrenia [5].

Concerning the working principle of the TMS appliance, a high current pulse in the coil device, placed above the scalp, produces a transient magnetic field involving the brain. The induced electric field having sufficient intensity in the conductive tissues causes indirect neuronal activation through synaptic inputs. The precise extent of neuronal activation is not known, but it clearly varies with the intensity of stimulation. There are different parameters that influence the effectiveness of the treatment. From the engineering point of view the TMS should be able to produce a good focality, repeatability, and to precisely target the stimulation. The so called figure-of-eight or butterfly coil is a cost-effective system with a good focality, although research in this direction is very active [6-7]. To improve the stimulation accuracy with respect to the manual gesture, robotics systems for TMS have been studied in recent years [8]. In this way it is also possible to obtain a repeatable positioning accuracy.

To produce a very focused stimulation showing, at the same time, a very small target, a comprehensive study must take into account the true shape of the coil and head. In particular the heterogeneity of the head tissues with their proper electric conductivity should be considered. This is a quite complex task, which allows the correct calculation of the distribution of the electric field and induced currents inside the brain. Examples of such an approach, based on finite element (FEM) computation, can be found in [9-11].

This paper addresses the problem through an approach based on the boundary element method (BEM) where the electric and magnetic fields on the discretized surfaces of each volume are the problem unknowns. The proposed technique is validated by comparison with the results provided by a FEM commercial code and applied to the evaluation of the induced currents flowing in a heterogeneous human head phantom.

II. Modeling Approach

Under sinusoidal conditions (angular frequency ω), the electromagnetic field problem is described by the Electric Field Integral Equation (EFIE) and Magnetic Field Integral Equation (MFIE). In the BEM approach the radiated body is divided into homogeneous volumes and the resulting bounding surfaces are discretized into quadrangles, where the electric and magnetic fields, assumed to be uniform on each element, are the problem unknowns. For a sub-volume **Ω**, bounded by *M* quadrangles, the field equations are [12]:

$$\xi \boldsymbol{E}_i = -\int_\Omega j\omega\mu\Psi \boldsymbol{J}_s dv - \sum_m^M (\boldsymbol{n}\times\boldsymbol{E})_m \times \int_{\partial\Omega_m} \nabla\Psi_{i,m} ds - \sum_m^M (\boldsymbol{n}\cdot\boldsymbol{E})_m \int_{\partial\Omega_m} \nabla\Psi_{i,m} ds + j\omega\mu \sum_m^M (\boldsymbol{n}\times\boldsymbol{H})_m \int_{\partial\Omega_m} \Psi_{i,m} ds$$

$$\xi \boldsymbol{H}_i = \int_\Omega (\boldsymbol{J}_s \times \nabla\Psi) dv - \sum_m^M (\boldsymbol{n}\times\boldsymbol{H})_m \times \int_{\partial\Omega_m} \nabla\Psi_{i,m} ds - \sum_m^M (\boldsymbol{n}\cdot\boldsymbol{H})_m \int_{\partial\Omega_m} \nabla\Psi_{i,m} ds - j\omega\tilde{\varepsilon} \sum_m^M (\boldsymbol{n}\times\boldsymbol{E})_m \int_{\partial\Omega_m} \Psi_{i,m} ds$$

where $\boldsymbol{J}_s$ is the impressed current density of the TMS coil, ξ is the singularity factor (ξ = 0.5 on the surface and ξ = 1 elsewhere), ***n*** is the normal unit vector directed outwards and μ, σ and ε are the magnetic permeability, the electric conductivity and the electric permittivity respectively. The Green's function is given by:

$$\Psi = \frac{e^{-ik|\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|} \quad \text{with } k = \omega\sqrt{\mu\left(\varepsilon - j\frac{\sigma}{\omega}\right)} = \omega\sqrt{\mu\tilde{\varepsilon}}$$

being ***r*** and ***r'*** are the coordinate vectors of the observation and of the source points. The two vectorial equations are then

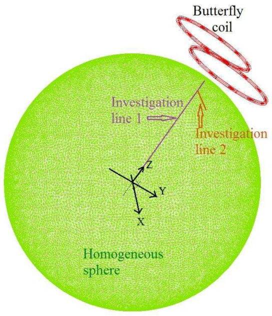

Fig. 1. Test problem

transformed into six scalar relations by projecting them on the local unit vectors defined for the *i*-th element. The resulting algebraic system is solved through GMRES, and the induced electric field is reconstructed in any point inside the body.

III. Validation and Result Analysis

The proposed procedure is first applied to a homogeneous sphere (σ = 0.1 S/m) radiated by a transcranial stimulation butterfly coil fed with a unitary magnetomotive force at 3 kHz (see Fig. 1). The same problem is also handled through the Finite Element code Opera 3D™. The agreement between the two results is excellent, as summarized in Fig. 2, where the behaviors along two test lines of the magnetic field and induced current density are presented.

The BEM procedure is then applied to a model of a simplified human head derived from the Standard SAM phantom and constituted by four regions [13] whose electrical properties correspond to the ones of skin (σ = 0.002 S/m, ε_r = 1100), skull (σ = 0.02 S/m, ε_r = 1200), brain (σ = 0.1 S/m, ε_r = 67000) and muscle (σ = 0.33 S/m, ε_r = 98000), evaluated at the supply frequency of 3 kHz [14]. The magnetic stimulation is generated by the same butterfly coil as in the previous case; the device is placed at 15 mm from the head (see Fig. 3). The same figure presents the distribution of the induced currents computed in the medium *z-y* cross section of the head, where the prevailing component of the magnetic field is along the *x*-axis. A more detailed investigation including other kind of coils (e.g. spiral coils) and voxel-based head models will be presented in the full paper with the aim of quantifying the reachable targeting capabilities.

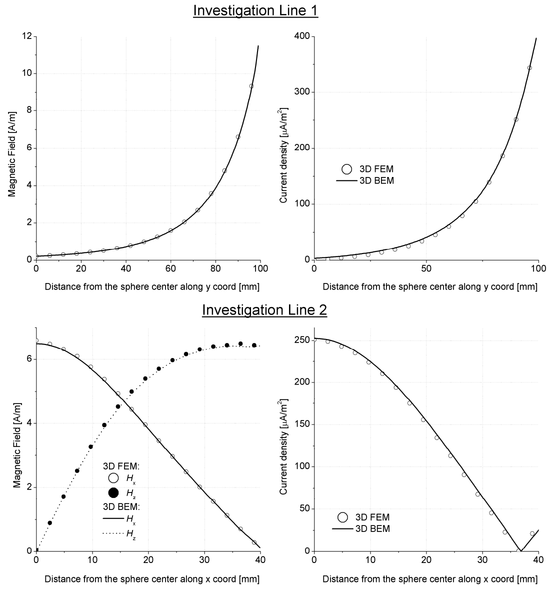

Fig. 2. Magnetic field and induced current density along the investigation lines computed by the BEM and FEM techniques

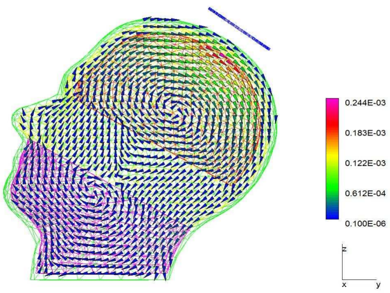

Fig. 3. Current density distribution produced by a butterfly coil in the medium *x-y* cross section of the head (A/m^2)

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