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A hybrid FE–BE method for SAR estimate in voxel based human models undergoing MRI

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ABSTRACT

The paper discusses the application of a hybrid Finite Element–Boundary Element technique to the electromagnetic dosimetric analysis of voxel based human models, with particular attention to the Magnetic Resonance Imaging appliances. A rational organization of the large amount of data involved by the voxel anatomy is presented to reduce the computational burden. The most suitable choice of the unknowns and the possible simplifying assumptions are also investigated. A hybrid Finite Element–Boundary Element approach is derived from the previous considerations, underlining the procedure for the system solution adopted when the whole algebraic matrix exceeds the RAM capabilities. The work is completed with some examples of applications.

1. Introduction

The analysis of the interaction between electromagnetic fields and human tissues is of increasing interest both in medicine, with the aim of extending diagnostic and therapeutic methodologies (e.g. Magnetic Resonance Imaging (MRI), transcranial magnetic stimulation (TMS), etc.), and as a support to verify the compliance with regulatory limits for the exposure of population and workers. In particular, induced electric field and Specific Absorption Rate (SAR) represent the basic restrictions established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), respectively in the frequency range between 1 Hz and 10 MHz [1] and in the frequency range between 100 kHz and 10 GHz [2]. Since direct dosimetric surveys are unfeasible in vivo, the studies are developed following two lines. In the first one, measurements are performed making use of suitably shaped plastic containers (phantom) filled with appropriate tissue equivalent liquids or gels which emulate the human body or a portion of it. A typical example is represented by the Specific Anthropomorphic Mannequin (SAM) adopted in the verification of mobile phone compliance with standards [3]. Alternative approaches are based on the numerical solution of the electromagnetic field problem applied to human models whose complexity is increasing during the years. The two ways of analysis are complementary, because the measurements on phantoms can validate the computational methods and, on the other side, the results of numerical simulations can confirm that the values recommended for the dielectric properties of the tissue equivalent fillers are conservative. References to phantoms and computational methods have been explicitly included in many technical standards and largely addressed in the literature, as detailed in the following.

An important evolution for the dosimetric analysis of human exposure to radiofrequency (RF) electromagnetic sources arose starting from the 1990s, with the diffusion of anatomical human models based on voxel data-sets which are obtained through Magnetic Resonance Imaging [4]. Nowadays, a number of anatomically and electrically detailed human models are available, such as the Virtual Family, or the HPA NORMAN and NAOMI data sets [5,6].

The use of voxel body models, which imply a dramatic increase of the unknown number, has led to the development of specific numerical techniques suitable for performing electromagnetic simulations (see for example [7–9]). In particular, the high number of degrees of freedom (DOF) favors the methods which do not require the solution of algebraic systems whose size is linked to DOF. The finite difference time-domain (FDTD) method has been largely used [10–13] for many applications like energy absorption calculations under far-field [14] and near-field [15–17] exposure. FDTD technique is also explicitly cited in several standards related to human exposure to RF electromagnetic fields [18–20]. Widely diffused commercial software based on FDTD are SEMCAD [21] and XFdtd [22].

Successful approaches are also based on the finite integration technique (FIT) [23–26], implemented in the general purpose high frequency commercial software CST Microwave Studio [27].

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However, as a drawback, these techniques cannot directly handle open boundary domain, so that the volume between the sources and the human model must be discretized, and the introduction of artificial boundary conditions is required. To overcome this problem, other approaches based on hybrid techniques have been proposed in the literature, as for example the coupling between the Finite Element Method (FEM) and the Method of Moments (MoM) [28].

The Boundary Element Method (BEM) is well suited for solving large 3-D open boundary problems and in addition, in virtue of the Green function, it guarantees a smooth reconstruction of the solutions so that it is adopted when high accuracy in field reconstruction is needed, as for example in MRI coil design [29]. Even if BEM has not been frequently applied to the evaluation of human exposure to electromagnetic fields, some successful applications of Boundary Element technique to dosimetric studies in the presence of homogenous or weakly heterogeneous phantoms can be found in [30–35]. Within this context, a BEM approach has been also recently proposed to simulate a voxel-based human body, adopting a Central Processing Unit–Graphical Processing Unit (CPU–GPU) implementation [36].

In this work the authors discuss the implementation of a frequency-domain formulation for the dosimetric analysis of RF fields in MRI, adopting highly heterogeneous voxel-based human models. The computational procedure makes use of a hybrid BEM/FEM technique, which takes advantage of the intrinsic capability of the Boundary Element Method in handling open boundary domains. Particular attention is devoted to the improvement of the efficiency and the accuracy of the numerical solution, by investigating the field equations and the simplifying assumptions, the numerical processing and the possible combination with other computational methods. A first problem concerns a rational organization of the formidable amount of data included in a detailed voxel anatomy, in order to limit the size and the non-zero elements of the associated matrix. Another aspect involves the choice of the most appropriate electromagnetic unknowns (fields/potentials, nodal/surface quantities). A final problem to be deepened is the method to solve the complex and non-symmetric system of equations, taking into account that often the number of non-zero entries can exceed the RAM capability of the computer. All the proposed approaches make explicitly reference to highly heterogeneous voxel-based anatomic models. The analysis of homogeneous or weakly heterogeneous domains (e.g. phantoms) could be more conveniently developed following different strategies, which are out of the scopes of this work.

The paper is organized as follows. In the next section, different strategies to efficiently handle the anatomic voxel data-sets are discussed, mainly in relation to the number of non-zero matrix entries, and the diverse choices of problem unknowns are examined. Starting from the previous considerations, a time periodic electromagnetic field formulation based on a hybrid FEM/BEM technique is adopted as the most advantageous from a computational point of view. This approach, presented in Section 3, is developed in terms of vector and scalar potentials. Section 4 gives some hints about the numerical implementation of the proposed hybrid FEM/BEM formulations on GPUs systems, with specific attention towards the case when the number of entries exceeds the RAM capabilities. Finally, Section 5 shows some examples of applications.

2. Preliminary considerations about domain structure and problem unknowns

The improvement of the efficiency in the computational tools used for simulating the field distribution in highly heterogeneous domains divided into voxels requires a preliminary investigation to select the most convenient approaches able to handle so large problems.

In order to organize and process the great amount of voxel data for the electromagnetic analysis, in principle two possible strategies can be adopted. In the first case, the entire voxel structure is processed preserving all the geometrical quantities (faces and nodes) associated to each single voxel (strategy I). This solution maintains the fine voxel structure, essential for the development of the thermal problem that is often coupled with the electromagnetic field analysis in dosimetric studies. Alternatively, adjacent voxels filled by the same material can be joined together to form a unique homogeneous volume, so that only the faces and nodes belonging to the surfaces of created volumes are involved in the computations (strategy II). The adoption of the last approach requires preliminary operations on the voxels dataset and, obviously, the processing simplicity involved in a regular geometric structure is lost.

With respect to strategy II, strategy I introduces a much greater number of unknowns, which are linked to all faces or nodes. However, the number of non-zero matrix elements, which actually determines the computational burden, is a matter of discussion, because following strategy I the regular structure of internal voxels significantly limits the interactions between unknowns (i.e. the non-zero matrix entries), counterbalancing the increase of the unknown number.

In order to investigate this aspect, we assume a cubic domain divided into $N \times N \times N$ voxels with $NT = (N+1)^3$ nodes, N being on the order of some hundreds, as usual in the applications. The total number of voxel faces is $FT = 3(N+1)N^2$; $FE = 6N^2$ of them are external (that is, they separate the body from the free space), while the remaining $FI = 3(N-1)N^2$ are internal.

When adopting strategy I, the number of the DOFs and of non-zero matrix elements are fixed and independent of the homogeneity degree of the domain. Assuming to have u unknown quantities associated to each face (resp node), the problem will have uFT (resp uNT) DOFs. Moreover, since any face can interact only with 11 faces and any node with 27 nodes, the number of non-zero entries is on the order of u^2N^3 and it cannot exceed $11u^2FT \cong 33u^2N^3$ and $27u^2NT \cong 27u^2N^3$ for faces and nodes, respectively.

The estimate becomes more difficult when considering strategy II, because the number and the shape of the homogeneous volumes created by the procedure depend on the size and distribution of the different materials which constitute the domain. However, two idealized arrangements can be exploited for a quantitative evaluation: a shell and a discretized structure. The shell structure is composed of concentric cubes, one internal to the other, to form a layered system. The most external layer, which can mimic the skin of a body, separates the external $N \times N \times N$ cube from an $L \times L \times L$ cube, where L is less than N, but close to it. The number of interactions between the faces included in this layer (and also the number of non-zero elements) is given by $u^2(6N^2+6L^2)^2 \cong 144u^2N^4$. Thus, also disregarding the other layers, the matrix entries depend on u^2N^4. A similar result is obtained by making reference to the nodes. In the discretized structure the $N \times N \times N$ cube is divided into $n \times n \times n$ smaller cubes, each of which includes $(N/n)^3$ voxels, where $1 < n < N$ and usually on the order of ten or some tens. In this case, the total number of interactions between the faces (both external and internal) is $\sim u^2N^4[36+(33/n)]$, so that it depends again on N^4. Similar considerations can be extended to the nodes.

In conclusion, the strategy I, which preserves the voxels, involves a greater number of unknowns, but gives rise to a significantly less populated matrix (proportional to N^3) with respect to strategy II (non-zero elements proportional to N^4). The