Dyadic Green Function/MoM based Method for the Analysis of Electromagnetic Fields inside a Lossy, Multilayered Spherical Head Phantom Excited By RF Coil

F. Liu[1], S. Crozier[1], B. Xu[1], I. Gregg[1]

[1]School of Information Technology and Electrical Engineering, Brisbane, Queensland, Australia

Synopsis

The precise evaluation of RF coil-tissue interactions and the electromagnetic fields (EMFs) inside biological samples is becoming an increasingly critical design requirement for high-field MRI engineering. Suitable phantom-based analysis is essential to coil design and evaluation. This paper presents an analysis model of RF coils in the presence of a multi-layered lossy sphere, roughly resembling the human head. The advantage of using this construct is that the fields can be calculated relatively quickly while maintaining realistic overall loading. In this model, the EMFs are handled by the dyadic Green's function (DGF) and the coil currents are evaluated by method of moments (MoM). Test examples show the capability of the proposed model.

Introduction

In high-frequency RF resonator design and analysis, a problem that has been of significant concern is electromagnetic interactions (EMI) with the human head. To investigate the safety issue and the field characteristics, a number of invaluable head models/phantoms have been developed [1-4]. As the human head is more like a stratified spheral structure, a multilayered spherical model might effective in addressing this EMI problem while maintaining computational speed. We therefore introduce a generic spherical model which can be divided to be an arbitrary number of concentric spherical layers each with different electrical properties. This method accounts for the coupling between the coils and head phantom, which is essential in near field analyses. After the EMFs are calculated, various imaging or antenna parameters can be straightforwardly investigated.

Dyadic Green's Function (DGF) /MoM Based Solutions for Arbitrarily shaped/positioned RF coils

The EMFs inside a layered spherical head phantom as shown in Fig.1 are modelled using the DGF technique. The DGF is a dyad that relates a vector field to a vector current source [5], and is constructed on spherical wave functions that satisfy vector wave functions in spherical coordinates. In this work, all the DGFs refer, by example, to the electric-fields. The magnetic fields can be determined by invoking duality. According to the principle of superposition, the EMFs inside and outside the layered sphere can all be expressed by the DGF as $G(r,r') = -\hat{r}\hat{r}/k_0^2\,\delta(r-r') + G_0(r,r') + G_s^{(L)}(r,r'), r > a;\ \ G(r,r') = G_s^{(l)}(r,r'), l = 0\mathrm{L}\ \ L-1,\ \ r \le a$ Where $-\hat{r}\hat{r}/k_0^2\,\delta(r-r')$ is an explicit dyadic delta function term, which specifies the singularity of DGF at the source point. The source is at location r' and field point is r ; $G_0(r,r')$ is the Green's function in free space, $G_s(r,r')$ is the scattering components: $G_s^{(l)}(r,r') = \sum_{n=1}^{+\infty}\sum_{m=0}^{n}[C]_{(1\times4)}^{(l)}\left[M_{mn}^3(r,k^{(l)})M_{mn}^3(r',k_0)\ \ N_{mn}^3(r,k^{(l)})N_{mn}^3(r',k_0)\ \ M_{mn}^1(r,k^{(l)})M_{mn}^3(r',k_0)\ \ N_{mn}^1(r,k^{(l)})N_{mn}^3(r',k_0)\right]^T, l = 0 \sim L$ where l denotes the layer number, [C] is the unknown expansion coefficients matrix; $[MN]_{mn}^{(l)}$ is the matrix of the spherical wave functions. To determine the expansion coefficients based on the continuity of the EMF components at the layer interfaces, one can obtain the following matrix series: $[A]_1^{(l)}[C]^{(l)}=[A]_2^{(l+1)}[C]^{(l+1)},\ l=0\sim L-1$ where $[A]_1$,$[A]_2$ are expressed by the Bessel/Hankel functions. After rewriting this linear equation series into matrix form, the following equation results: $\left[A\right]_{(4L\times4L)}^{n}\left[C\right]_{(4L\times1)}^{n} = \left[0\right]_{(4L\times1)}^{n}$,where $[A]$ is a sparse matrix and the elements are expressed by $[A]_1$, $[A]_2$. All the expansion coefficients can be obtained directly by matrix-inversion. The next step is to determine the coil currents by the MoM [6], without losing generality, thin-wire conditions are only considered here. To determine the coil currents, the wire is subdivided into N segments and the triangular basis functions are employed along wire elements. After performing "testing' for each basis function, the EMF integral equation is transformed into an MoM matrix equation: [Z][I]=[V]. Where [Z] is the impedance matrix, [V] is the voltage vector. The coil currents [I] can be obtained by matrix inversion. Once the currents are obtained, the EMFs can be calculated by and integral of the DGFs and coil currents. As EMFs are available, one can evaluate all the antenna and imaging parameters. It is noted that in MoM section, the perturbation of the coil currents by the loads is accounted for and can be used with RF coils of arbitrary shape or position.

Simulations

To show the capability of the proposed method, a RF coil/phantom interaction case has been investigated with the configuration of Fig.1. The head phantom was a 4-concentric sphere volume conductor, representing brain, CSF, skull and scalp tissues. The electromagnetic data of the human head used in this work was obtained from the US Air Force Research Laboratory (http://www.brooks.af.mil/AFRL/HED/hedr/). The radius of the coil was 6 cm, the coil/sphere distance was 8 cm, and the radius of the sphere was 8 cm. The RF source was an input voltage (amplitude: 1 volt, phase: 0°), and only linear polarization was considered at this stage. The MoM calculations were performed using the electromagnetic module of the EMF package FEKO (http://www.feko.co.za). Firstly, we set up the resonant circular loop by introducing four capacitors distributed equally along the coil. The value of each capacitor was initially determined by considering the resonance of the LC circuits, and then modified through MoM calculations. When the spherical phantom was "loaded", the resonance frequency was shifted and hence the capacitor values were "tuned" to make the coil resonant at 64MHz as depicted in Fig.2. The comparison between the DFG/MoM solutions and the Debye potential (DP) [6] based results was also carried out. In DP calculations, a predefined current distribution along the surface coil was derived from the MoM evaluations, where the effect of the head model was also included. As shown in Fig.1, the two methods generated similar results. Fig.3 showed the H-field profile (470MHz) and reflects the effect of the inclusion of the highly-contrasted conductivity profiles on the H-field distribution.

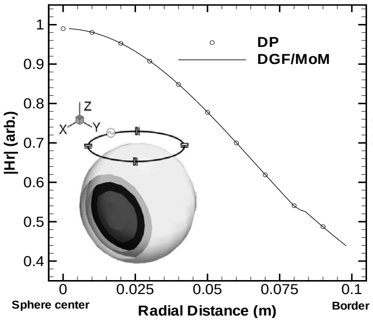

Fig.1. Comparison of the DP and DGF/MoM solution for the H-fields in the sphere along the radial distance at y=0. For the DP solution, the coil current was "predefined" by MoM.

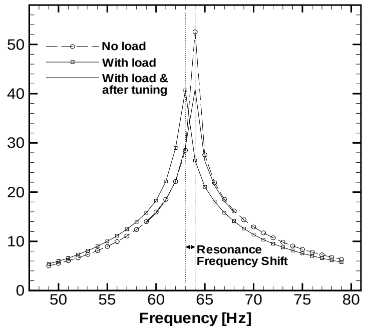

Fig.2. Reflection coefficient (S_{11}) vs Frequency. When the resonance frequency was shifted after loading, the capacitors were "tuned" to make the coil resonant at the desired frequency.

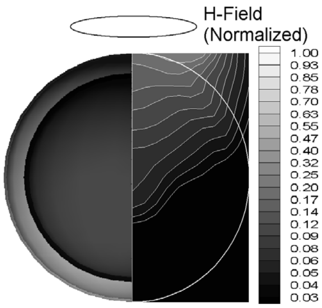

Fig.3. The H-field profile in the sphere in x=0 plane (see. Fig.1) .

Conclusion

The proposed DGF/MoM hybrid approach enables one to assess the loading effects upon the operating characteristics of the RF coils and also the field behaviour inside the objects. It is anticipated that this model will be of value for high frequency RF resonator optimization.

References

[1] Hoult & Phil, J Magn Reson Imag., 12: 46-67 (2000).
[2] Keltner, Carlson, Roos, Wong , Wong & Buninger, Magn Reson Med., 22: 467-480 (1991).
[3] Collins, et al., Magn Reson Med. 47: 1026-1028, (2002).
[4] Strilka et.al., Magn Reson Imag, 16(7): 787-798 (1998).
[5] Tai, Dyadic green functions in electromagnetic theory, 2nd ed. New York: IEEE Press, (1994).
[6] Jin, Electromagnetic analysis and design in magnetic resonance imaging, CRC, (1999).