The basis functions: a novel approach for electromagnetic fields evaluations for any matching and coupling conditions

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Purpose. 3D full-wave numerical techniques permits the Electromagnetic (EM) characterization of radio-frequency (RF) fields, namely the E and B1 field, and the calculation of the SAR distribution, as well as the S parameter matrix. In most of the cases, it is difficult to have access to the actual matching networks and to correctly reproduce them in the simulation; thus, it follows that the simulated S parameter matrix can be quite different from the actual one. RF fields and SAR distributions depend on the S parameter matrix: in [1] it has been shown that a simple phase-variation in some Sxy elements of the S matrix can lead to a SAR increase up to 30%. The use of 3D full-wave tools by itself becomes a severe limiting factor in the analysis multi-port MR coil when the anatomic human model is included in the simulation domain, because the full 3D EM problem must be solved for each matching and coupling condition (note that a multi-port MR coil can be either a volume coil driven in quadrature, or a coil for parallel transmission). Alternatively, two-way link between RF circuit and 3D EM simulation tools can be employed [2]: this enables simulation results from the RF circuit domain to be used to drive the 3D EM domain. Two-way link requires to substitute all the lumped elements with ports with impedance of 50 ohm. Here we propose a different procedure which can be summarized as follows:

i.) The tuned coil with the anatomic human model is simulated by modeling the feeding using equivalent ports with impedance of 50 ohm as sources for a given matching and coupling condition (without removing any lumped elements); S parameter matrix and RF fields are computed at the operating frequency.

ii.) The RF field basis functions, i.e. the RF fields produced by each individual ports without any residual coupling, are derived through an algebraic procedure.

iii.) For any other S parameter matrix, i.e. for any matching and coupling condition, the RF fields are calculated as appropriate combination of the basis functions.

The procedure permits to quickly evaluate RF fields inside an anatomic human model under different matching and coupling condition. The proposed approach can be therefore used both for volume coil driven in quadrature and for any parallel transmission configuration. Here, it has been validated by using a 7.0 T volume coil driven in quadrature loaded by an anatomical human head.

Methods. The first step for extracting the RF fields basis functions is to simulate the tuned coil with the anatomic human model through a 3D full-wave numerical tool, modeling the feeding using equivalent ports with impedance of 50 ohm as sources for a given matching and coupling condition (without removing any lumped elements). Thus, if we have N sources, the S parameter matrix will be N×N.

The N RF fields are computed at the operating frequency. Let us indicate with: $\underline{\boldsymbol{E}} = \left[\vec{E}^{1}, \vec{E}^{2}, ..., \vec{E}^{N}\right]^{T}$, $\underline{\boldsymbol{B}}_{\boldsymbol{1}} = \left[\vec{B}_1^{1}, \vec{B}_1^{2}, ..., \vec{B}_1^{N}\right]^{T}$ (1)

the 1×N array constituted by the vector E and B1 RF fields, respectively, produced by the sources on a given grid of points. The RF fields contain residual coupling between the other ports as would be the case in physical system. Let us now indicate with:

$$\underline{\boldsymbol{\psi}}_{\boldsymbol{E}} = \left[\vec{\psi}_E^{1}, \vec{\psi}_E^{2}, ..., \vec{\psi}_E^{N}\right]^{T}, \underline{\boldsymbol{\psi}}_{\boldsymbol{B_1}} = \left[\vec{\psi}_{B_1}^{1}, \vec{\psi}_{B_1}^{2}, ..., \vec{\psi}_{B_1}^{N}\right]^{T} \quad (2)$$

the 1×N array constituted by the vector basis functions for E and B1 RF fields, i.e. they represent the vector fields produced by each source which do not contain the residual coupling between the other ports. It holds: $\underline{\boldsymbol{E}} = \left(\underline{\underline{\boldsymbol{S}}} + \underline{\underline{\boldsymbol{I}}}\right) \cdot \underline{\boldsymbol{\psi}}_{\boldsymbol{E}}$, $\underline{\boldsymbol{B}}_{\boldsymbol{1}} = \left(\underline{\underline{\boldsymbol{S}}} + \underline{\underline{\boldsymbol{I}}}\right) \cdot \underline{\boldsymbol{\psi}}_{\boldsymbol{B_1}}$. (3)

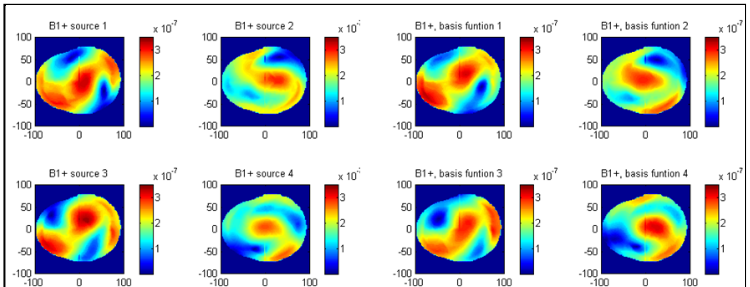

Fig 1. (1[st]-2[nd] col.) Magnitude of B_1^+ produced by the 4 sources when applying 1 W of input power at each source; (3[rd]-4[th] col.) Magnitude of the 4 basis function of B_1^+. Magnitude is in T, x/y axis are given in mm.

In eq. (3), $\underline{\underline{\boldsymbol{S}}}, \underline{\underline{\boldsymbol{I}}}$ denotes the S parameter matrix and the identity matrix.

Thus the basis function at the operating frequency and on a given grid of points can be determined as: $\underline{\boldsymbol{\psi}}_{\boldsymbol{E}} = \left(\underline{\underline{\boldsymbol{S}}} + \underline{\underline{\boldsymbol{I}}}\right)^{-1} \cdot \underline{\boldsymbol{E}}$, $\underline{\boldsymbol{\psi}}_{\boldsymbol{B_1}} = \left(\underline{\underline{\boldsymbol{S}}} + \underline{\underline{\boldsymbol{I}}}\right)^{-1} \cdot \underline{\boldsymbol{B}}_{\boldsymbol{1}}$. (4)

Once the basis functions have been determined, the RF fields can be quickly computed for any other S parameter matrix by applying eq. (3), i.e. avoiding any other 3D full-wave simulation.

$$\underline{\underline{S}} = \begin{bmatrix} 0.28e^{-j1.21} & 0.16e^{-j3.08} & 0.58e^{-j1.38} & 0.16e^{-j3.09} \\ 0.16e^{-j3.08} & 0.43e^{-j1.22} & 0.13e^{-j3.04} & 0.44e^{-j1.37} \\ 0.58e^{-j1.38} & 0.13e^{-j3.04} & 0.33e^{-j1.13} & 0.14e^{-j2.93} \\ 0.16e^{-j3.09} & 0.44e^{-j1.37} & 0.14e^{-j2.93} & 0.44e^{-j1.22} \end{bmatrix} \quad (5)$$

Results. The procedure has been validated considering a volume coil loaded by an anatomical human head. Specifically, we resorted to CST MW Suite to simulate a shielded 16 elements 1H high-pass birdcage head coil manufactured by Nova Medical (Wilmington, MA, USA), operating in quadrature at 298 MHz. The coils has been loaded by a human head extracted from the 2×2×2 mm^3 voxel-size anatomic human model Billie (Virtual population, ITIS foundation). Quadrature feeding has been employed by using 4 sources having equal input power, equally azimuthally displaced by $\pi/2$, with a relative electrical phase shift of $\pi/2$. The coil has been tuned to 298 MHz and matched using a capacitive matching circuit obtaining the S parameter matrix given in eq (5). In the CST simulations, 12.5 million mesh node have been used (simulation time= 48 hours on one 3.10GHz/32GB-RAM workstation). The RF fields produced by the four sources and computed at the 298 MHz and on the axial slice crossing the eyes are calculated when applying 1 W of input power (at each source); the magnitude of counter-rotating components of B1 (i.e. B_1^+) is shown in Fig. 1, 1[st] -2[nd] col. For the sake of brevity, the others components of B1 and the components of E are not shown here. Fig. 1, 3[rd]-4[th] col. shows the vector basis functions for B_1^+. With the aim of validating the procedure, we performed another 3D full-wave simulation with different matching and coupling conditions: this was achieved by reducing three times the matching capacitors, leading to a S parameter matrix which differs from eq (5). The B_1^+ field produced by the latter simulations is given in Fig. 2a. Fig. 2b instead, shows the B_1^+ fields obtained by the using of eq. (3).

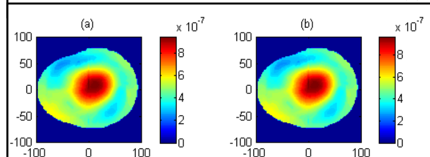

Fig 2. Magnitude of B_1^+ for a different matching and coupling condition: (a) full wave simulation; (b) calculation performed by employing eq. (3), i.e. by resorting to the basis functions. Magnitude is in T, x/y axis are given in mm.

Discussions and Conclusion. By comparing the basis functions with the fields produced by the single ports it is possible to quantify the impact of the residual coupling: here, we observed that residual coupling affects especially the fields produced by source 4 with a relative modification of the maximum of the magnitude up to 15%. The residual coupling is removed through an algebraic procedure which uses the S parameter matrix and the RF fields calculated in the first (and only) full-wave simulation; this allow to calculate the RF field basis functions which can be used as building-blocks for calculating the RF fields for any other S parameter matrix. In this context, an excellent agreement can be observed by comparing Fig. 2a and Fig. 2b. Specifically, the average relative error is lower than 3%. It follows that, once the basis functions have been determined, the RF fields can be quickly determined for any other S parameter matrix by applying eq. (3), i.e. avoiding any other 3D full-wave simulation. We remind the reader that this holds true if the effects of fringe fields of capacitors and other lumped elements are neglected. If the measured S parameter matrix is available, it can be used in eq. (3), allowing the procedure to provide an insight into the realistic RF fields distributions.

References. [1] Kozlov M et al, Proc ISMRM, 2013, p.2830. [2] Kozlov M et al, JMR. 2009-200(1), pp 147-52