Electro-Dynamic Inverse Method for High-Field RF Transmit Coil Design

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Introduction: MRI radio-frequency (RF) transmit coils need to produce homogeneous transverse magnetic fields. At low field strengths in the human head, this is typically accomplished by birdcage-like transmitters. At field strengths of 7T and above, it is believed that due to destructive wave interferences, producing homogeneous fields by a single resonator is no longer possible. Several alternative approaches are therefore being explored to improve transmit uniformity at high field. Here we present a general full-wave electro-dynamic approach that allows one to find current distributions on surface conductors that generate homogeneous field distributions over specified region of interest inside a human head model. Thus theoretically, homogeneous fields can still be produced by a single coil structure, at least at 7.0 Tesla. Inverse approaches have been taken to design Bo field gradients (1) and RF coils for lower field strengths (2).

Methods: This method starts with specifying a surface (or multiple surfaces) where currents can flow and the locations where field uniformity is required. In Figure 1, the current surface is denoted in red and homogeneous fields are desired on multiple axial slices denoted in cyan. The target current distribution is unknown and can be expanded by a set of *N* basis functions as in Eq. (1). Since we applied triangular patches to model the arbitrarily shaped current surface, RWG basis functions were used. However, arbitrary currents may exist but can not be readily implemented by closed conductors. To remove the part of the currents not implementable by conduction currents, we applied the Helmholtz decomposition and combined the RWG basis functions into two types of basis functions, i.e., solenoidal (or loop) and irrotational (or star) types. Star basis functions represents displacement currents caused by the time-varying local charges. Therefore, they are discarded and we only retain the loop basis functions.

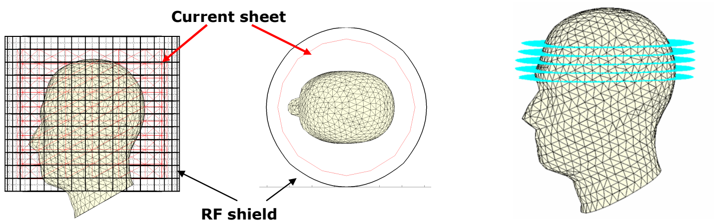

Fig. 1: Specified current surface (left) and the axial locations for homogeneous field excitations (right).

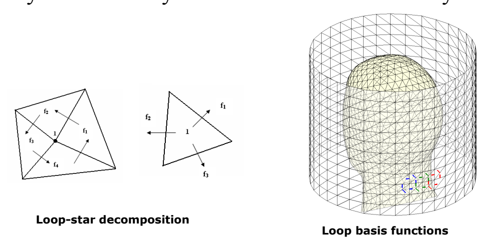

Fig. 2: Helmholtz decomposition of current basis functions (left) and the remaining loop basis functions (right).

The fields generated by each loop basis function can be used as the basis to expand the desired homogeneous fields as in Eq. (2). Note that the unknown coefficients are the same in Eq. (1). One can apply Galerkin's method and test Eq. (2) at the desired locations. In this way, a set of linear system equations can be established and solutions can be found by matrix inversion. In general, this linear system is ill-conditioned and Tikhonov regularization should be applied.

$$\vec{I}_{target} = \sum_{j=1}^{N_{Loop}} I_j \cdot \vec{L}_j \qquad (1) \qquad\qquad \vec{B}_{target} = \sum_{j=1}^{N_{Loop}} I_j \cdot \vec{B}_j \qquad (2)$$

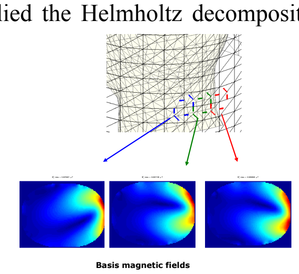

Fig 3: Fields generated by each loop current.

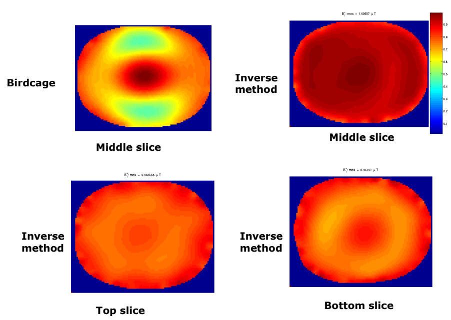

Fig 4: 7.0 Tesla fields generated by a birdcage coil and ideal current distribution found by inverse method on three axial slices.

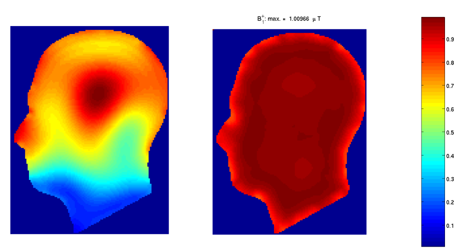

Fig 5: 7.0 Tesla fields generated by a birdcage coil and ideal current distribution found by inverse method on sagittal slice.

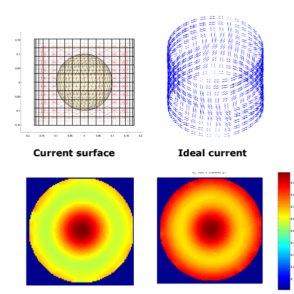

Fig 6: Inverse approach for a spherical phantom at 7.0 Tesla.

Results and Discussion: Figures 4 and 5 illustrate the field distributions produced by a birdcage coil and ideal currents on different slices at 7.0 Tesla. In general, the ideal current distribution depends on the specification of target fields and looks quite different for the cases in Figs. 4 and 5. Furthermore, it also depends on the shape of the phantom and the desired degree of complexity, which translates into the number of loop basis functions applied to expand the unknown current distribution. For instance, Fig. 6 shows the ideal current distribution for generating homogeneous fields in a spherical phantom by applying eight loop basis functions. It is observed that the resulting field is less homogeneous due to the reduced degrees of freedom. However, the current distribution is easier to follow and interestingly shows a spiral pattern. The practical solution is a tradeoff between current complexity and field homogeneity. In theory however, there exist current distributions that can produce homogeneous B1 fields at high field strengths. The challenge is now to realize these current distributions in a physical structure.

Conclusion: We presented an inverse approach based on full-wave electro-dynamics for determining desired current distributions for targeted field distributions. This approach is applicable to arbitrarily shaped conductor surfaces and human-shaped phantoms.

References: 1) R. Turner, J. Phys. E: Sci. Instrum., vol.21, pp. 948–952, 1988. 2) BG. Lawrence et.al. IEEE TBME, vol. 49, pp. 1024-1030, 2002.