Theoretical design of shim arrays with irregular coil geometry

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Target audience: This design concept will be of interest to those working on shim coil development, shim/gradient arrays and novel spatial encoding methods.

Purpose: In conventional MRI systems, a set of shim fields is used to correct for unwanted distortions in the B_0-field. Typically, these fields are generated actively using shim coils, whereby each coil is responsible for generating a particular spherical harmonic field term.[1] However, due to space constraints within the scanner, it is normal to include only up to the second-order shim coils, and this limits the accuracy to which the field distortions can be corrected. Recently, an alternative shimming method has been proposed, in which the spherical harmonic shim coils are replaced by a large number of circular loops arranged uniformly on a cylindrical former.[2] These coils provide a substitute set of basis fields that, while not orthogonal, potentially afford additional degrees of freedom for field matching. In this work, we explore the merit behind using circular loops and propose that significant gains in field accuracy and efficiency can be made using irregular coil geometry.

Methods: The first aim was to design a shim array tailored toward generating the three first-order spherical harmonic field terms and compare its performance to that of an array of circular loops. A second array was also designed tailored toward generating the five second-order terms for additional comparison. While this approach may appear in conflict to the fundamental concept behind shim arrays (i.e. their departure from spherical harmonics considerations), these low-order fields nevertheless provide a logical basis for assessing field accuracy and efficiency.[2] Furthermore, since the new designs still fulfil the primary shim array requirement of consisting of multiple independent elements, they still afford equivalent degrees of freedom for higher-order field correction.

A cylinder of length 0.06 m and radius 0.015 m was considered (oriented with the z-axis) in line with other work.[2] The surface was divided into 24 sub-regions of equal size forming a 6×4 array in ($\theta \times z$). An independent current density vector $\boldsymbol{j}_{kq}(\theta,z)$ was considered in each subregion (k=1:6, q=1:4) and represented using Fourier series. Collectively, these current density vectors were optimized to induce a given target field within a spherical volume of interest of radius 0.008 m, centred at the origin. This optimization was performed separately for each of the three first-order and five second-order spherical harmonic terms. Power minimization was used to regularize the problem to a degree that the induced field had an average volumetric field error of 1% in each case. The first-order shim array was obtained by summing the magnitudes of the streamfunctions associated with the three first-order current density vectors in each subregion, followed by contouring to yield the winding positions. This method provides no guarantee of an optimal solution; however, since the streamfunctions contain information regarding the optimal geometry for generating the component spherical harmonic terms, the expectation was that the result would nevertheless retain geometrical aspects that are superior to using circular loops. The second-order array was obtained in a similar fashion after considering various weightings in the streamfunction sum. For comparison, an array consisting of circular loops was also designed, with 5 identical loops per subregion, and the loop radius was chosen accordingly to match the total winding length of the irregular geometry arrays. For a given spherical harmonic target field, the 24 coil currents were obtained using least squares fitting (MATLAB). Constraints on peak current magnitude were applied to assess the trade-off between coil efficiency and field accuracy for each array.

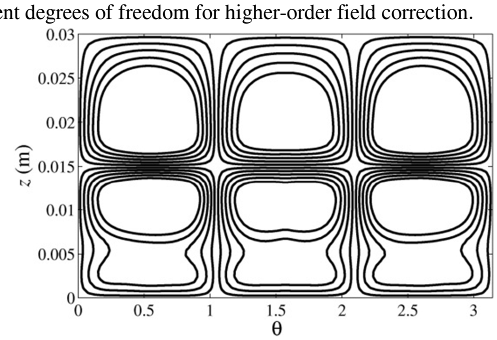

Fig.1: First-order irregular shim array (one quadrant).

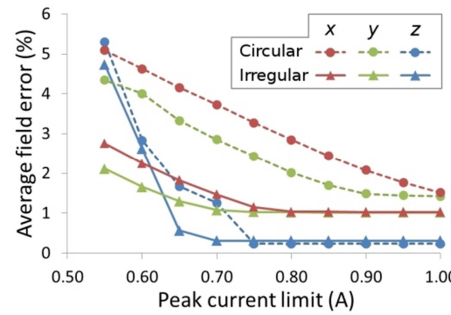

Fig.2: Accuracy/efficiency trade-off: first-order.

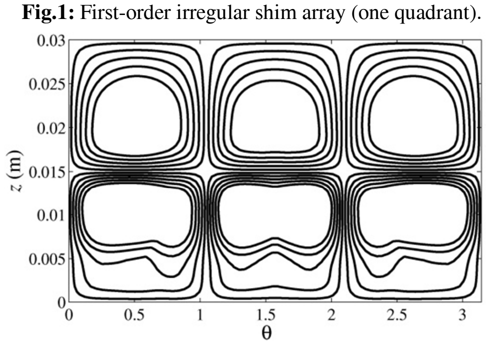

Fig.3: Second-order irregular shim array (one quadrant).

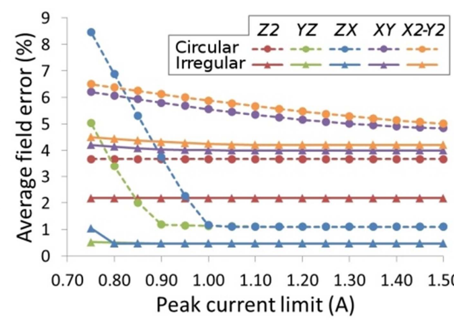

Fig.4: Accuracy/efficiency trade-off: second-order.

Results: Fig. 1 displays the coil windings in one quadrant (i.e. 6 sub-regions) of the first-order irregular shim array (symmetric about z=0 and $\theta=\pi$). This array is capable of inducing a 5 mT/m (2.13 kHz/cm) x-, y- or z-gradient with an accuracy of 1.03%, 1.01% or 0.31% average volumetric field error, with a peak current of 0.85 A, 0.99 A or 0.67 A and a total current sum of 8.40 A, 9.24 A or 8.76 A, respectively. In contrast, the corresponding array of circular loops provides an accuracy of 1.42% (x), 1.42% (y) or 0.24% (z), with a higher peak current of 1.07 A, 1.22 A or 0.72 A and a higher current sum of 9.87 A, 11.02 A or 9.56 A, respectively. Fig. 2 displays the expected accuracy associated with each array for a constrained peak current ranging from 0.55-1.0 A (a similar plot is obtained when constraining the current sum instead). Fig. 3 shows the coil windings in one quadrant of the second-order shim array. In Fig. 4, the expected accuracy of this array for generating 500 mT/m^2 (2.13 kHz/cm^2) second-order field terms is compared to that of the array of circular loops, given a constrained peak current ranging from 0.75-1.5 A.

Discussion: With the exception of the z-gradient field, in all cases the arrays with irregularly shaped coil elements were found to be capable of generating fields (up to second-order) of significantly higher accuracy than the circular loop arrays and, importantly, these required lower peak and total currents. Indeed the improvement in field accuracy was most notable as peak (or total) current was constrained, as demonstrated in Figs. 2 and 4. While current limitations are tied inherently to amplifier technology, lower field error measures allow higher field strengths to be generated accurately within these limitations. Of course, one clear advantage with using circular loops is the simplicity of fabrication. Nevertheless, the windings displayed in Figs. 1 and 3 are of a smooth and regular nature amenable to copper etching, for example. While the two arrays share a similar general form, the specific geometry is tied strongly to the weighting of the component streamfunctions and, in this regard, the search performed in this study for an optimal set of weightings was by no means exhaustive. Indeed in subsequent analysis an unexpected finding was that the second-order array was in fact capable of generating first-order fields to a higher degree of accuracy than the first-order array. This suggests that considerable further gains may be possible using shim arrays with irregular geometry, following a comprehensive survey of weightings or a reformulation of the optimization problem.

References: [1] Romeo F, Hoult DI. Magnet field profiling: analysis and correcting coil design. *Magn. Reson. Med.* 1984; 1:44-65
[2] Juchem C, Nixon TW, McIntyre S, Rothman DL, de Graaf RA. Magnetic field modeling with a set of individual localized coils. *J. Magn. Reson.* 2010; 204:281-289