Towards a Complete Coil Array

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Introduction

The invention of the MRI array coil [1] drastically improved the signal-to-noise ratio (SNR) of MR images and lead to accelerated image acquisition with sensitivity encoding (SENSE). Recently, a large array of receiver coils has been demonstrated in brain imaging [2]. The calculated intrinsic SNRs for the current coil technologies are still significantly below the ultimate intrinsic SNR near the surface regions of the object [3]. It has been pointed out that a "complete coil system" is needed for achieving the ultimate intrinsic SNR [4-6] based on the principle of reciprocity [7]. A complete coil system is capable of generating any steady-state RF field at the MR frequency that is compatible with Maxwell's equations. Therefore, a coil system is complete if it is capable of generating all basis vector fields in the multipole expansion of the electromagnetic fields. Here, we demonstrate that an array coil may be configured to approximate a complete array coil and generate the basis magnetic vector fields up to certain orders.

Method

An array coil with elements located at the 60 vertices of a truncated icosahedron (shape of a soccer ball) is considered. The center of coil system coincides with the magnet's center, and one of the pentagons in the truncated icosahedron is parallel with the xy-plane and located at the highest z-level with one vertex inside the xz-plane. The distance between the center of the magnet and all vertices is 20 cm, and the RF field is calculated in a 10 cm radius sphere at the magnet's center. There are three current loops centered in each vertex, with axes along x, y, and z directions, respectively [8]. The current loops are small in size, so they can be treated as magnetic dipoles. The entire space is filled with a loss-less medium with $\varepsilon = 80$, and the frequency of the RF field is 298 MHz (the proton MR frequency at 7 T). The simulation was carried out using IDL.

The multipole expansion vector fields $\mathbf{H}^{E}_{lm}$ and $\mathbf{H}^{M}_{lm}$ form a complete basis set for the steady-state magnetic field in a source free region [6]. If the magnetic field is finite at $r = 0$, these basis vector fields can be expressed as [9]:

$$\mathbf{H}^{E}{}_{lm} = \frac{1}{\sqrt{l(l+1)}} j_l(kr)\mathbf{L}Y_{lm}(\theta,\phi), \quad \text{and} \quad \mathbf{H}^{M}{}_{lm} = -\frac{i}{k\sqrt{l(l+1)}} \nabla\times j_l(kr)\mathbf{L}Y_{lm}(\theta,\phi) \qquad [1]$$

Here k is the amplitude of the wave vector. The magnetic field pattern arising from a current loop q of the array coil can be approximated by that of an oscillating unit dipole $\mathbf{m}_q$ located at $\mathbf{r}_q$ [9]:

$$\mathbf{H}^{d}_{q}(\mathbf{r}) = \frac{e^{ik|\mathbf{r}-\mathbf{r}_q|}}{4\pi|\mathbf{r}-\mathbf{r}_q|}\cdot\{[k^2 - (\frac{1}{|\mathbf{r}-\mathbf{r}_q|^2} - \frac{ik}{|\mathbf{r}-\mathbf{r}_q|})]\cdot\mathbf{m}_q - [k^2 - 3\cdot(\frac{1}{|\mathbf{r}-\mathbf{r}_q|^2} - \frac{ik}{|\mathbf{r}-\mathbf{r}_q|})]\cdot(\mathbf{n}\cdot\mathbf{m}_q)\mathbf{n}\}, \quad \text{with} \quad \mathbf{n} = \frac{\mathbf{r}-\mathbf{r}_q}{|\mathbf{r}-\mathbf{r}_q|} \qquad [2]$$

The dipole fields of the array elements were used to construct the target vector fields $\mathbf{H}^{E}_{lm}$ and $\mathbf{H}^{M}_{lm}$ (l = 1, 2, 3, …, m = -l, -l +1, …, l) using a least-squares procedure:

$$err = \sum_p |\sum_q C_q \cdot \mathbf{H}^{d}_{q}(\mathbf{r}_p) - \mathbf{H}_{\text{target}}(\mathbf{r}_p)|^2 = \text{minimum} \qquad [3]$$

Here, the sum is taking over current loops q and spatial points $\mathbf{r}_p$; C_q represents complex adjustable parameters (representing electric currents in 180 current loops); $\mathbf{r}_p$ is located on a cubic lattice with the nearest neighbor distance of 1 cm, and $\mathbf{r}_p$ is restricted to the region $|\mathbf{r}_p| \leq 10$ cm.

Results

The constructed fields using the dipole array are very close to the target $\mathbf{H}^{E}_{lm}$ and $\mathbf{H}^{M}_{lm}$ fields if l is not large (see the Figure below as one example). The errors of the constructed field are assessed by the spatial average of the residual complex vector field amplitude normalized by the spatial average of the target field amplitude. The table below lists the range of errors for all m values corresponding to a specific field order l. The errors are below 3% for $l < 6$. The errors increase as l further increases, when the angular density of the coil elements is no longer sufficiently large.

Discussion and Conclusions

A coil system that can generate all $\mathbf{H}^{E}_{lm}$ and $\mathbf{H}^{M}_{lm}$ fields is a complete coil system. This type of coil configurations has the potential to reach the ultimate intrinsic SNR as an MR receiver coil [4]. However, a truly complete coil array system would need an infinite number of array elements and is not practical to build. On the other hand, for detecting signals at the deep interior of an object, the gain from including increasingly higher order fields is limited [2,3]. This study demonstrates that with a large number of array elements, a complete coil array system can be approximately achieved for up to a certain order of the field. Here, we have assumed the medium is infinitely large and loss-less. Further studies will be needed for more realistic situations. Implementation of this type of array coil should lead to increase of the SNR of the MR signals, especially in regions near the surface.

Table. Range of errors of the constructed RF magnetic field by the magnetic dipole array.

Field order (l)	$\mathbf{H}^{E}_{lm}$	$\mathbf{H}^{M}_{lm}$
+	0.5 - 0.5%	1.4 - 1.4%
2	1.2 - 1.3%	0.9 - 2.2%
3	0.6 - 1.2%	0.9 - 1.8%
4	1.3 - 2.2%	1.1 - 2.0%
5	0.6 - 2.7%	1.4 - 2.4%
6	2.3 - 8.7%	2.5 - 3.8%
7	6.8 - 14%	4.1 - 8.0%
8	14 - 51%	9.1 - 20%

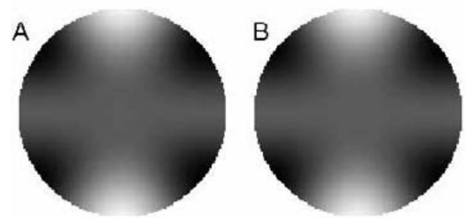

Figure. Real part of the x-component (y-axis is vertical) of the magnetic field in the z = 0 plane. A: the target field $\mathbf{H}^{E}_{43}$; B: the field generated by the array coil. The field is zero at the center where the image intensity is grey, and the black areas have negative values.

References: 1. Roemer PB et al, Magn Reson Med 1990: 16: 192-225; 2. Wald LL, Proc. Intl Mag Reson Med 2006: 14: 202; 3. Wiesinger F et al, Med 2005: 13: 672; 4. Ocali O et al, Magn Reson Med 1998: 39: 462-73; 5. Ohliger MA et al, Magn Reson Med 2003: 50: 1018–30; 6. Wiesinger F et al, Magn Reson Med 2004: 52: 376-90; 7. Hoult DI et al, J Magn Reson 1976: 24:71-85; 8. Wang ZJ et al, Concepts Magn Reson Part B (Magn Reson Engineering) 2005: 24B: 1–5; 9. Jackson JD, *Classical Electrodynamics*. 3rd ed. 1999