Design of a shielded coil element of a matrix gradient coil

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Target audience: Developers of innovative hardware and novel spatial encoding strategies for MRI.

Purpose: Spatial encoding with nonlinear magnetic fields (SEMs) has raised increasing interest in the past few years [1-3]. Matrix coils consisting of multiple coil elements [4] appear to offer a high flexibility in generating customized SEMs and are particularly promising for localized high resolution imaging applications such as PatLoc [1]. However, existing coil elements of those matrix coils were constructed to primarily for better shimming. They cannot achieve an optimal performance for local spatial encoding [5]. Moreover, eddy current implication of those coil elements were not fully explored. In this work, an optimization problem is formulated that results in novel designs of high-performance coil elements for an actively-shielded matrix gradient coil. Two parameters are proposed to assess the performance of different coil element designs. The results are tested and the analysis reveals new insights into coil element design.

Methods: The following design requirements of the coil element were considered: firstly, the coil element has to generate an encoding field with strong local gradients at every test point within a region of interest (ROI). Secondly, eddy current effects induced by operating the coil element should be reduced for artifact-free imaging. Finally, some engineering constraints, such as wire track width, have to be considered for the practical fabrication of the coil element.

Based on the requirements above, an optimization problem is proposed as follows:

$$\min_{\Phi} F,\quad F = -\sum_{\mathbf{x}_i \in ROI} \left|\nabla B_z(\Phi,\mathbf{x}_i)\right| + \alpha_e\left(\sum_{\mathbf{x}_i \in ROI}\left|B_z^e(\Phi,\mathbf{x}_i)\right|^2\right)^{1/2} + \alpha_J \left\|\mathbf{J}(\Phi)\right\|_p, \text{subject to } \frac{1}{\tau\sigma}\int_\Gamma |\,\mathbf{J}(\Phi)\,|^2 d\Gamma \le P_{\max}. \tag{1}$$

Here, Φ denotes the stream function of the electric current density vector $\boldsymbol{J}(\Phi)$ where $\boldsymbol{J}(\Phi) = \nabla\times(\Phi\boldsymbol{n})$ on a current-carrying surface Γ (Fig. 1) with a normal unit vector $\boldsymbol{n}$. The B_z and B_z^e are z-components of the magnetic fields generated by current $\boldsymbol{J}$ on Γ and induced eddy current $\boldsymbol{J}^e$ on a conducting layer S, respectively (Fig. 1). Here, according to [6], $\boldsymbol{J}^e$ is calculated by the formula $\boldsymbol{J}^e = -L_{ss}^{-1}L_{sc}\boldsymbol{J}$ where L_{ss} is the self-inductance matrix of the basis functions of electric current densities defined on S and L_{sc} is the mutual inductance matrix between basis functions of electric current densities on S and that on Γ. Those magnetic fields are calculated using the Biot-Savart law. The points $\mathbf{x}_i=(x_i, y_i, z_i)$, i=1, …, m, denote the coordinate vectors of m test points in the ROI, τ indicates the thickness of the surface Γ, σ is the electrical conductivity of the surface Γ, $P_{\max}$ denotes the maximal dissipated power of the designed coil element. The objective function F of the problem (1) consists of three terms. The first term is related to the gradient strength of the encoding fields, the second term is used to reduce the eddy current effect in the ROI and the third term is applied to control the minimal width of wire tracks of the designed coil element by the p-norm ($\|\cdot\|_p$) method [7]. Two positive constants α_e and α_J are used to balance the tradeoff among those three terms.

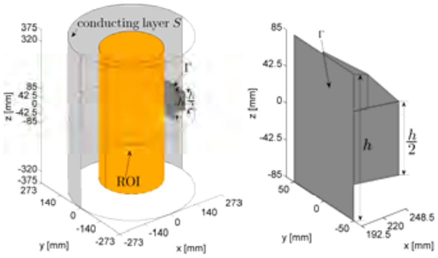

Figure 1: *Geometries of a current-carrying surface* Γ, *shielding layer S and ROI.*

In order to assess different single coil elements, two performance metrics are defined as follows:

$$\beta := \frac{\sum_{\mathbf{x}_i\in ROI}\left|\nabla B_z(\Phi,\mathbf{x}_i)\right|}{m\sqrt{P_{\max}}},\qquad \nu := \frac{\max_{\mathbf{x}_i\in ROI}\left|B_z^e(\Phi,\mathbf{x}_i)\right|}{\max_{\mathbf{x}_i\in ROI}\left|B_z(\Phi,\mathbf{x}_i)\right|}. \tag{2}$$

Here, the figure of merit β is used to measure the coil efficiency to obtain the average of gradients of the encoding field over the ROI and the shield ratio ν [8] is calculated to assess the effect of shielding the eddy current on the S. From equations (2), it is clear that an ideal high-performance coil element should have a high β and low ν.

All numerical examples were solved with the function *fmincon* in MATLAB (The MathWorks. Natick, USA). In these examples, the current-carrying surface Γ (Fig. 1) is located on a twelfth of a cylindrical ring along the circumference direction. The radii of inscribed and circumscribed cylinder of Γ are 191 mm and 250 mm. All the test points are located on the boundary of the cylindrical ROI (Fig. 1) with a radius of 140 mm and a height of 640 mm. The conducting layer S is a cylindrical surface with a radius of 273 mm and a height of 750 mm. These geometries correspond to dimensions of a head coil, which can be scaled-up to a whole-body coil. The τ, σ and $P_{\max}$ are set as 3 mm, 5.8×10^4 S/mm and 0.006 W respectively.

Results and Discussion: Figures 2(a-b) show a trade-off between low shielding ratios ν and high coil efficiency β. For a coil element with a fixed height, ν has a tendency to decrease on the whole with the increase of α_e although small increases of ν may occur in some cases. However, the corresponding β also decreases. These small variations of ν can be caused by a small incompatibility between definitions of the objective in (1) and ν. Figures 2(a-b) also illustrate that drastic reductions in ν and β can simultaneously occur with the increase of α_e. These reductions are caused by topologic changes of layouts of wire tracks indicated by contours of Φ. For example, for coil element designs with α_J = 0 and h = 170 mm, the shielding ratio ν (at α_e = 1500) was reduced by a factor of 5 (at α_e = 1600) and 98 (at α_e = 10000), while the corresponding β was reduced by a factor of 1.23 and 1.76. As shown in Figures 2(c-e), the corresponding layouts of the coil elements change from one center of rings to two centers to three centers with the increase of α_e. Based on those results, we propose to use the layout at α_e = 1600 as the basic layout for our coil element prototypes. In order to obtain realizable wire tracks, the minimal width of adjacent contours (Fig. 2(d)) was increased by a factor of 1.08 using α_J = 9e-5. The corresponding β and ν were slightly reduced by a factor of 1.03 and 1.05, respectively.

Conclusions: The proposed design method is useful to obtain a realizable coil element of a matrix gradient coil. Two performance parameters can be used to measure different coil element designs and assist a decision-maker to determine which coil element layout is suitable for their purpose.

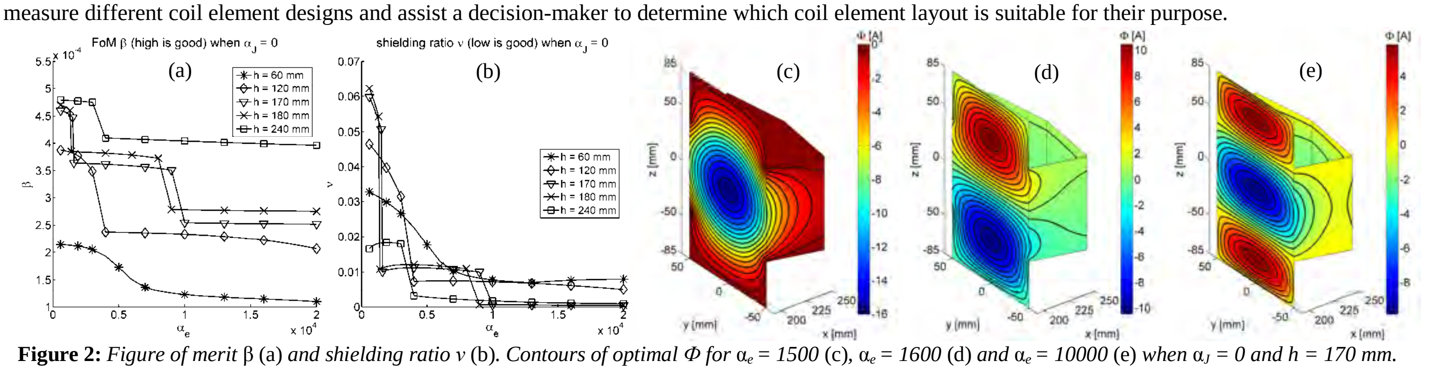

Figure 2: *Figure of merit* β (a) *and shielding ratio ν* (b). *Contours of optimal* Φ *for* α_e = 1500 (c), α_e = 1600 (d) *and* α_e = 10000 (e) *when* α_J = 0 *and* h = 170 mm.

References: [1] Hennig et al., MAGMA 2008;21:5; [2] Gallichan et al., MRM 2011, 65:702; [3] Layton et al., MRM 2013, 70:684; [4] Juchem et al., MRM 2011, 66:893; [5] Jia et al., Proc. ISMRM 2013, #666; [6] Peeren, J. Comput. Phys. 2003, 191:305; [7] Jia et al., Proc. ISMRM 2011, #3780; [8] Liu et al. JMR 2013, 226:70;

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