Can we re-design the gradient coil to make the eddy current field match the primary gradient field?

H. Sanchez[1], M. Poole[1], A. Trakic[1], and S. Crozier[1]

[1]Research Group/Affiliation: EMI, School of Information Technology & electrical Engineering, Brisbane, QLD, Australia

Introduction: Rapidly switched magnetic field gradients induce eddy currents in the nearby conducting structures of the MRI scanner. These eddy currents in turn generate an opposing and distorting transient magnetic field in the region of interest (ROI) with consequential image distortion. A tailored current pulse is usually applied to minimize the undesired effects of the eddy currents in the ROI. In order to successfully apply this current compensation technique, the primary and the secondary magnetic field produced by the eddy currents should have a similar spatial form in the ROI (*field matching*). Some efforts have been made to improve the linearity of the secondary and hence maximize the field matching figure [1,2]. In this work we present two approaches for gradient coil design that produces gradient fields with characteristics similar to those produced by the eddy currents. The first approach iteratively refines the gradient coil so that its primary field is similar to the induced secondary field. The second approach, termed as the mode coil [3], classifies as an eigenvector assignment [4] technique. The mode coil [3] produces maximal field matching with a large field non-linearity. This limitation is improved by designing an actively shielded mode gradient coil. The presented examples are used to demonstrate the advantages and disadvantages of the proposed techniques.

Step 1 generate s_0^S **FIG. 1**

Step 2: *For k = 1:M*

$$\mathbf{c}^S \tilde{s}_k^{\,S} \le -\mathbf{G}^C \mathbf{U} e^{-\lambda t^T} \mathbf{U} \tilde{s}_{ind}^{\,C}(\tilde{s}_0^{\,S}, t^T)(1+\alpha)$$

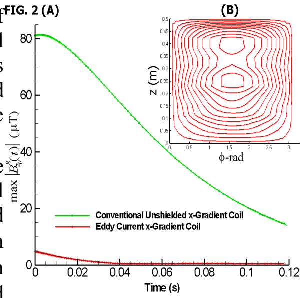
$$-\mathbf{c}^S \tilde{s}_k^{\,S} \le \mathbf{G}^C \mathbf{U} e^{-\lambda t^T} \mathbf{U} \tilde{s}_{ind}^{\,C}(\tilde{s}_0^{\,S}, t^T)(1-\alpha)$$

Step 3: $\tilde{s}_0^{\,S} = \tilde{s}_k^{\,S}$, update $\mathbf{M}_{S-C}$

Step 4: if mean(I_k)≤error end else go to **Step** 2

Method: It is assumed that a 15 mm thick aluminum cylinder (surface C) of radius 377.5 mm and half length of 550 mm surrounds a cylindrical coil surface S of radius 320 mm and half length of 500 mm. When a low-frequency driving current is applied to the gradient set, the skin depth is very small under the aforementioned assumption, and therefore a superficial induced current density can be assumed. No fields leak through the surface C. Experimental validation of the eddy current model was performed [2].We used the "free-surface" gradient coil design method EMC [5] to design the coil and to perform the transient eddy current analysis using Runge-Kutta integration method [2]. A residual field figure defined as $B_z{}^R{}_x(\mathbf{r},t)=I^{pre}(t)B_z(\mathbf{r},t)^{coil}- u(t)B_z(\mathbf{r},t)^{coil}+B_z(\mathbf{r},t)^{Eddy}$ was used to measure the coil performance in terms of how much undesired field remains in the ROI when an $I^{pre}(t)$ tailored current pulse is applied. u(t) is the original current pulse and $B_z(\mathbf{r},t)^{Eddy}$ is the secondary field.

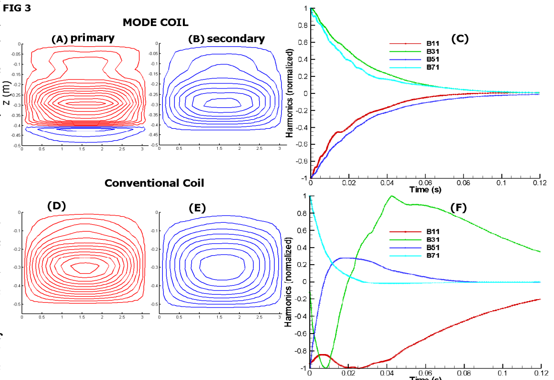
FIG. 2



Eddy Current Gradient Coil (ECC): In this approach the resultant coil is a consequence of matching the primary field to the secondary field for a given target time t^T. The pseudo-code showed in Fig. 1, describes the method using a semi-analytical solution of the eddy current for a step-Heaviside current pulse. $\mathbf{c}^s$, $\mathbf{G}^C$ are the matrices that contain the magnetic field contribution from surfaces S and C, within the ROI. **U**,**λ** are the Eigen modes and values of surface C; $\mathbf{s}_0^S$ is the stream function of the initial coil, designed to produced the gradient G_0^{Target} with a relaxing factor ε [5] (step 1).$\mathbf{s}_{ind}^C$ are the stream function values of the induced eddy current in surface C, α is the error that defines the field matching quality between the primary and secondary field. The current factor I_k is the operating current to generate the target gradient. In step 2, a new gradient coil is designed such that the gradient field cancels the secondary field generated by the previous coil. At the same time however, this new coil induces new eddy currents in C, hence the mutual coupling matrix $\mathbf{M}_{S\text{-}C}$ must be re-computed to take the change in the coil pattern into account. The process is repeated until the change I_k is smaller than a pre-defined error. The linear constraints in **Step** 2 are included in a quadratic programming (QP) optimization problem [5].

Gradient Coil design using Eigenmode assignment: An Eigenmode coil is designed to only excite one of the modes of the eddy current in the conducting surface C and suppress all others. This design is refereed to as the *mode* coil [3]. The solution of the diffusion equation $\mathbf{M}_{C\text{-}C}d\mathbf{s}_{ind}^C/dt+\mathbf{R}_{C\text{-}C}\mathbf{s}_{ind}^C=-\mathbf{M}_{S\text{-}C}d\mathbf{s}^S(t)/dt$ for a step-Heaviside current pulse is expressed as [6] $\mathbf{s}_{ind}^C(t)=\mathbf{U}\exp(-\boldsymbol{\lambda}t)\mathbf{U}^{-1}\,\mathbf{s}_{ind}^C(t^{0+})$, where $\mathbf{M}_{C\text{-}C}$ and $\mathbf{R}_{C\text{-}C}$ are the self inductance and resistance matrices. $\mathbf{s}_{ind}^C(\mathbf{s}^S,t^{0+})=-\mathbf{M}_{C\text{-}C}^{-1}\mathbf{M}_{S\text{-}C}\mathbf{s}^S$ assuming that $\mathbf{s}_{ind}^C(t^0)=0$. The highlighted expression dictates which of the eigenmodes in C are excited by the source current $\mathbf{s}^S$. Each mode excited by $\mathbf{s}^S$ has its own decay constant; it may therefore be desirable to excite only one mode by an appropriate design of the coil current pattern $\mathbf{s}^S$. For this purpose, the following linear constraints are included in the EMC QP problem [5]. ($\mathbf{s}^S$ is an unknown vector):$\mathbf{U}^{-1}\mathbf{s}_{ind}^C(\mathbf{s}^S,t^{0+})\le \mathbf{U}^{-1}\mathbf{s}_m^C+\beta$,$-\mathbf{U}^{-1}\mathbf{s}_{ind}^C(\mathbf{s}^S,t^{0+})\le -\mathbf{U}^{-1}\mathbf{s}_m^C-\beta$, where $\mathbf{s}_m$ is the target mode selected from the eigenmode matrix **U**, and β is an error that defines the accuracy in exciting the target mode. In this way, the spatial form of the secondary field and the primary field is dictated by the mode $\mathbf{s}_m^C$. Therefore, both fields have the same spatial characteristic and only one time constant is presented in the eddy current decay. However, the field linearity of the secondary field is larger than the usually 5% deviation from the lineal target field. We implemented the mode coil strategy for multi-layer surfaces S and we investigate the effect over the primary field linearity.

FIG 3



Results and Discussions: Figure (2) shows (**A**) the maximum $B_z{}^R{}_x$ figure of a conventional *x*-gradient coil when a tailored pre-emphasis $I^{pre}(t)$ pulse is applied. u(t) is a step-Heaviside function. A maximum of 80 μT is obtained due to the lack of spatial matching between the primary and secondary field. The field matching figure is measured as a maximal linear deviation of the secondary field (scaled in magnitude) relative to the primary gradient field. For the conventional coil, changes of 4% to 11% during the pulse duration were observed. The *x*-ECC (Fig. 2 **B** one quarter is illustrated) field matching figure in the *x*-ECC coil changes from just 0.6% to 0.8% which results in a maximal $B_z{}^R{}_x$ figure of 5 μT in the first few milliseconds. The FoM (η^2/L) of the *x*-ECC was 2 times larger than that which is produced by the conventional coil; however the field non-linearity was 5 times larger in the *x*-ECC coil. This nonlinearity is one of the limitations of the ECC coils. The secondary field is naturally not as linear as the primary field, even when the primary coil produces a very uniform gradient in the ROI. The secondary field is a consequence of the magnetic field contribution of the excited modes. One way to improve this limitation may be re-shaping the conducting surface C [2]. Another limitation of the *x*-ECC coil is that they are designed for a single target time (in this example we set t^T=30 ms) and it is possible that for a different target time then the coil pattern changes. However, if the initial coil $\mathbf{s}_0^S$ excites few modes in C, then the *x*-ECC coil will keep approximately the same current pattern during the pulse; this is the case for the coil presented in Fig 2 which produces a minimal residual field during the pulse when $I^{pre}(t)$ is applied. The number of excited modes increases when a very linear primary field is specified (small ε). The current overshoot is around two in both cases. A single layer mode coil produces maximal field matching and a linearity of the same order as generated by the ECC coils [3]. To improve the linearity of the primary field and still excite only one mode, we designed an actively shielded mode coil. Figure (3 **A** and **B**), shows an actively shielded mode coil with control over the magnitude of the secondary field in ROI. A solution exists if the secondary field value is constrained to a small value in the ROI. Therefore, no field matching is required because $B_z(\mathbf{r},t)^{Eddy}\approx 0$ and the QP algorithm is able to find a solution where a set of modes is excited and combined in such a way that the target mode is maximized while the others are minimized. Figure (3 **C** and **F**) shows the transient analysis of the spherical harmonics generated by the secondary field. Fig 3 (**F**)shows a complex spatio-temporal field change in the ROI (conventional coil (**D** and **E**)), while the harmonics generated by the mode coil decay exponentially in time. Since $B_z(\mathbf{r},t)^{Eddy}\approx 0$, the overshoot current is nearly 1. In both designs the maximal $B_z{}^R{}_x$ figure was around 2 μT and the FoM of the mode coil was 2.4 smaller than the conventional coil. The maximal harmonic amplitudes in both coil designs were in order of micro Tesla.

Conclusions: We have presented two alternative methods for gradient coil design. The first approach produces gradient coils where the primary field possesses similar spatial form as the secondary field. The ECC coil produces superior performance than the conventional coil: larger FoM and minimal residual field when a tailored current pulse is applied. The second method uses an eigenmode technique to design an actively shielded mode gradient coil with improved primary field linearity and less complex spatio-temporal secondary field than the conventional actively shielded coil. Although the mode coil is less efficient than the conventional coil, it produces a 2.5 times smaller magnetic field in surface C than the conventional coil.

References: [1] Heid O , et al 2003, Patent (USA: 6,531,870). [2] H. Sanchez, et al, submitted to ISMRM 2010. [3]M. Poole, et al, submitted to ISMRM 2010.[4] Hong B. et al, IEEE Trans Magn. **32**, 1996. [5] H. Sanchez-Lopez, et al., J, Volume 199, Issue 1, p. 48-55,2009. [6] Peeren GN. 2003 Journal of Computational Physics;191:305–321.**Acknowledgements:** Financial support from the Australian Research Council is gratefully acknowledged.