Using shape optimization to linearise the eddy current field

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Introduction: MRI requires rapidly switched magnetic field gradients. This time-dependent magnetic fields induce eddy currents in nearby conducting structures. These currents generate detrimental transient magnetic fields in the region of interest (ROI) and hence, active and/or passive shielding and current compensation is required to minimize the consequential image distortion. In order to apply successfully current compensation techniques, it is required that the primary and the secondary magnetic fields possess a similar spatial form in the ROI. In this work we investigated by simulation, the effect of re-shaping a highly conducting passive shield surrounding a gradient coil (and the gradient coil surface) over the matching field for optimal current compensation. We define a matching field figure as the relative linear deviation of the eddy current field to the primary gradient field. A residual field figure is included in an objective function OF and is minimized simultaneously for both *x* and *z*-gradient coils assuming a single frequency time-harmonic current. A conducting surface with a bulge has previously been suggested [1].

Method: We used the "free-surface" gradient coil design method EMC [2] to optimize the coil and to perform the eddy current transient analysis using Runge-Kutta integration method [3]. A trapezoidal fuzzy function was used to parameterize the coil/conducting surface. The optimization process includes several evaluations of the self $\mathbf{M}_{C\text{-}C}$ and mutual $\mathbf{M}_{S\text{-}C}$ inductive coupling matrix every time that the surfaces are modified. We assumed the inductive coupling between the discrete coil segments and the continuous conducting surface in order to speed up the evaluation of the $\mathbf{M}_{S\text{-}C}$ matrix, hence no Gauss-Legendre integration is required [2]. In case of time-harmonic analysis using a single exciting frequency, ω, the induced eddy current $\mathbf{s}^{ind}$ is related with the stream function of the coil $\mathbf{s}^{coil}$ by $\mathbf{s}^{ind}=-j\omega(j\omega\, \mathbf{M}_{C\text{-}C}+ \mathbf{R}_{C\text{-}C})^{-1}\, \mathbf{M}_{C\text{-}C}\, \mathbf{s}^{coil}$, where $\mathbf{R}_{S\text{-}C}$ is the self-resistance matrix of the conducting surface C. In order to maximize the field matching figure and at the same time minimize the inductive coupling between the coil surface S and the conducting surface C we defined the OF as $\min(\max(|B_z{}^R{}_x|,|B_z{}^R{}_z|))$ where $B_z{}^R{}_x$ is the residual field figure of the x(z)-gradient coil defined as $B_z{}^R{}_x(\mathbf{r},t)=I^{pre}(t)B_z(\mathbf{r},t)^{coil}- u(t)B_z(\mathbf{r},t)^{coil}+B_z(\mathbf{r},t)^{Eddy}$ where $I^{pre}(t)$ is the tailored current pulse, u(t) is the original current pulse and $B_z(\mathbf{r},t)^{Eddy}$ is the secondary or eddy current field. The optimization can be performed using a single frequency approach or applying long current pulse and selecting a set of target time values. To simplify the optimization, we used a single frequency ω=1 kHz. Three coil scenarios where studied and compared with an unshielded no surface modified coil (A) and an actively shielded coil (B) with eddy current control over the DSV [2].In case C, the conducting surface was free to deform while the coil support was fixed. In case D the coil support surface was reshaped for a fixed conducting surface. In case E, the conducting surface and coil support are simultaneously modified. We used as surface C a 15 mm thick aluminum cylinder of radius 377.5 mm and half length of 550 mm. The surface S (coil surface) was a cylinder of radius 320 mm and half length of 500 mm.

Validation: Experimental validation of the eddy current simulations was attempted by construction of an unshielded model z-gradient coil (radius 125.5 mm, half length 180 mm) and 2.6mm-thick aluminum cylinder (radius 175mm, half length 193mm). Field measurements were made on axis using a magnetic tunnel junction (MTJ) magnetoresistive sensor [4] with a 15 ms flat-top trapezoidal current pulse and 2 ms ramp-up and down in the coil. Simulations were performed with the EMC[2] software on the same coil with the same current pulse for comparison. Fig1. Shows the good agreement between the measured B_z(r=0,z=4 mm) and the predicted field. A 5 % difference in field magnitude was found due to the accuracy of sensor placement.

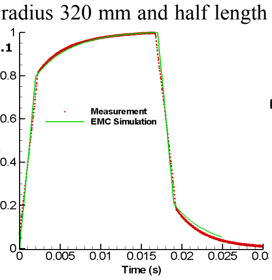
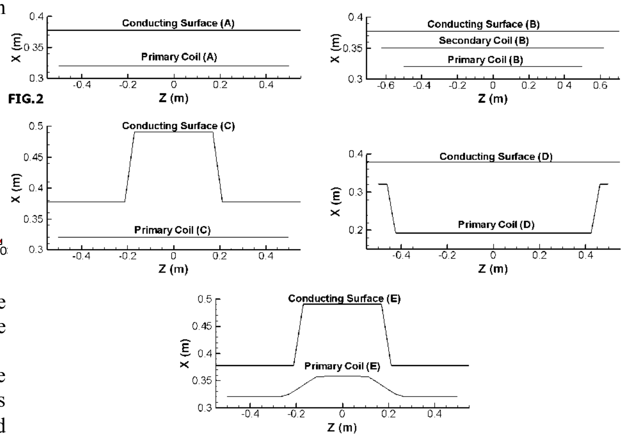
FIG.1


FIG.2


Results and Discussions: Figure 2, shows the profiles of the studied coils with surface modifications (C, D and E). The current overshoot of coil (A) was 1.56 times the basis current u(t) to produce 10 mT/m and the residual field figure was 72.09 µT and field matching was 6.87%. In coil B the current overshoot was 1 and around 2.86 µT was the residual field ($B_z{}^R{}_x$) for the set frequency. The field matching in coil C was 1.1%, the current overshoot was 1.35 while $B_z{}^R{}_x$ =6.48 µT. In case D the overshoot was 1.13 and $B_z{}^R{}_x$ =28.45 µT. In case E, showed in Fig. 3, the field matching was 0.52%, the current overshoot was 1.39 and $B_z{}^R{}_x$ =3.08 µT. In the cases of coils using shape modification the best coil performance in terms of minimal $B_z{}^R{}_x$ and maximal field matching was case E; case D is not practical if the coil is used for whole body imaging. Design B produces the smallest $B_z{}^R{}_x$ and overshoot current due to the eddy current control at the DSV [2].When using passive shielding to produce minimal residual field figure it is clear that a mechanism to reduce the OF is to create a bulge in the conducting surface *C*. In this case, the stream function of the induced eddy current has similar spatial characteristic of the primary stream function on surface *S*. The bulge created in surface *C* minimizes the amplitude of the spherical harmonic A_{31}; that is the first non linear harmonic that contributes to the non linearity of the secondary field in the ROI. As well, the mutual coupling between the coil and the surface *C* is reduced and hence a minimal overshoot current is required. In case E, the coil surface tended to move towards surface *C* in order to produce the required and optimal field matching. However, the conducting surface *C* moved away from the coil such that the mutual inductive coupling is reduced to minimize the overshoot current. From time-harmonic analyses cases B and E produces similar $B_z{}^R{}_x$; however when transient analysis (see Fig. 4 A) if performed we realize that after few milliseconds the $B_z{}^R{}_x$ figure increases in cases C and E and the reduction in $B_z{}^R{}_x$ is around 5 times from the original value produced by design A and 4 times larger than the actively shielded coil B. This implies that optimal bulge shape is not compensating the harmonic A^E_{31} as it was minimized for the time-harmonic approach. This phenomenon is well depicted in Fig. (4 B). The harmonic A^E_{31} affects the residual field figure after few milliseconds. The relaxing factor played an essential role in our approach. When the optimization algorithm resulted in a large relaxing factor (~0.1) the primary coil current pattern was spread out and a low current density region at the centre of the coil was created. As a consequence, the induced eddy current pattern possessed a similar current profile to that of the primary coil and good field matching results.

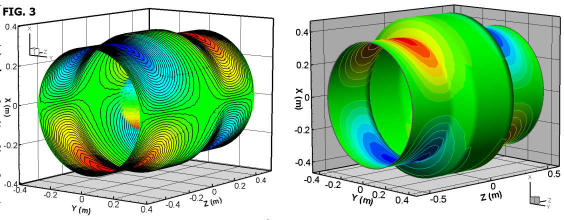
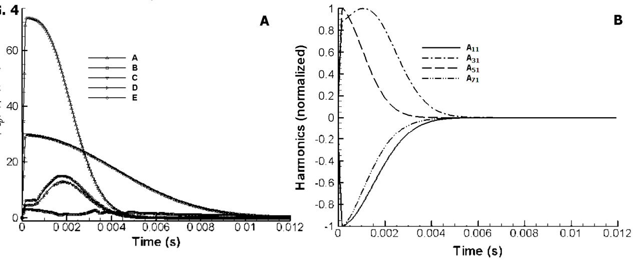
FIG. 3


FIG. 4


Conclusions: We studied the effect of re-shaping a conducting and/or coil support surface on the residual field figure for spatially-improved eddy current compensation by simulation. Using a highly conducting surface $B_z{}^R{}_x$ was reduced up to 5 times the residual field figure from an original non optimized *x*-gradient coil when a realistic current pulse was used. Similar residual field values were obtained for jointly optimized *x* and *z*-gradient coils. Although the surface shapes were optimized using a single frequency time-harmonic approach, a maximal matching field with minimal inductive coupling was obtained for single layer unshielded gradient coils for time-varying pulses. Transient analysis demonstrated that due to the A_{31} spherical harmonic, the residual field figure increases for those cases where a bulge is created in the surface. Active shielding produces superior control over the magnitude of the residual field figure.

References: [1] Heid O and Vester M 2003, Patent (USA: 6,531,870). [2] H. Sanchez-Lopez, et al., Journal of Magnetic Resonance, Volume 199, Issue 1, p. 48-55,2009. [3] M. Clemens, et al**,** Proceedings of ENUMATH 2007, Graz, Austria, September 2007. [4] STJ-201, Micro Magnetics, Inc. Fall River, MA

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