Simulation and experimental verification of eddy current due to RF coil shielding

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Introduction: RF shielding can improve transmit efficiency, reduce SAR, and increase Signal Noise Ratio (SNR) significantly. It is very important for MRI RF coil design, especially for ultra-high field 7T MRI applications. Nevertheless, RF copper shielding induced eddy current could be very problematic. There are patents and papers discuss shielding slots method to reduce eddy currents [1, 2]. Less reported is the quantitative eddy current study. Analytically, eddy currents are notoriously difficult to calculate. In this present work, we simulate the eddy current distorted gradient field. Successful MRI field experiment validation is also delivered. Eddy current characterization is studied based on eddy current response function.

Methods: Coil and Experiments: A 4-element Tic-Tac-Toe coil [3] was constructed and five sides head-long rectangular copper RF shielding was positioned around the Tx/Rx coil to increase the SNR. The assembled coil is shown in Figure1.The thickness of the RF copper shielding is 18µm (half oz copper sheets). The field raw data was acquired on a 7T Siemens scanner. In order to measure gradient field with eddy current distortion, calibration gradient waveforms were applied multiple times with different amplitudes and at different slice locations. **Simulation:** The 7T Siemens MRI whole body gradient coils were designed using Stream Function Method. The gradient has 5% gradient homogeneity around 40 cm in X, Y, and Z directions. The gradient coils, Tic-Tac-Toe coil and 18µm copper shielding models were constructed in SolidWorks. In the ANSYS Maxwell 14.0 Transient solver, the coil model was imported and eddy current distortion was simulated. **Eddy Current Characterization**: The eddy current characteristics could be demonstrated by the eddy current response function H(t) [4, 5, and 6]. H(t) was modeled as the sum of multiple exponential terms with constant time and variable amplitude parameters in this work. The eddy currents induced magnetic field could be derived as the convolution of the negative time derivative of the ideal gradient field and the eddy current response function H(t). In order to fit the eddy current response function (H(t)), magnetic field distributions were simulated with and without Tic-Tac-Toe coil in the ANSYS Transient solver.

Figure1 Tic-Tac-Toe transmit/receive coil

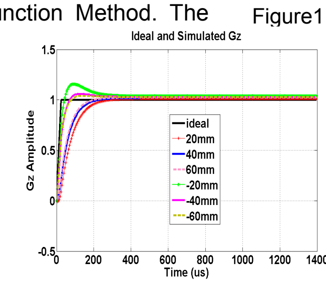


Figure2 simulation results

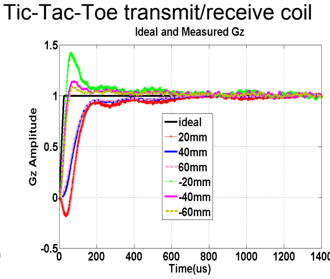


Figure3 measurement results

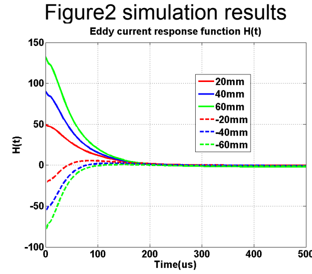


Figure4 response function

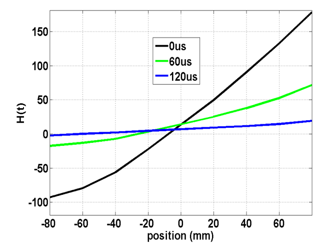


Figure5 H(t) at different positions

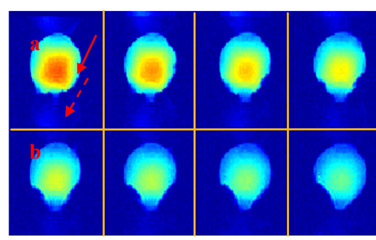
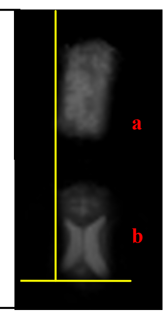


Figure6 EPI phantom images

Figure7 localized excitation images on human subject



Results and Discussion: Figure2 displays results from simulation. It shows a comparison of the ideal gradient strength Gz and the real gradient strength at different positions along Z direction, which is defined as (B0/ γz). The positive direction is in the direction of the head and the negative direction is in the direction of the feet. The ideal gradient ramp up time is 30us. From Figure2, we can notice that Gz is deviating from the ideal Gz at the beginning and becomes stabilized and equals to Gz after several hundred micro seconds (~200us). Therefore, this ramp up time is significantly increased by the eddy current effects. The gradient field strength/distribution is noticeably distorted and is non-linear along Z direction. It also shows that ramp up time and magnetic field strengths distortion is asymmetric for the positive and negative direction because of the existing of cap copper shielding on top of the coil. Figure 3 shows the measured gradient waveform at different positions. The ramp up time of the measured gradient trajectory was increased to ~200us which agrees well with the prediction form the simulation. The experimental results also demonstrate that eddy current distortion is not linear along the Z direction and asymmetric as those shown in Figure2. There are some minor discrepancies: the slight oscillating between 200us to 600us measured in experiments was not in the simulation, which worth further investigation.

To study the effects of eddy current at different locations, the eddy current response function H(t) obtained from simulation results are presented in Figure4. It shows that the eddy current response functions H(t) have different characteristics for positive and negative directions. Figure5 demonstrate that H(t) is not a linear function. The eddy current effects are more prevalent in positive 60mm position than the negative 60mm position as shown in Figure5: H(t) is (-80,-13, 0) at -60mm and (133, 55, 15) at 60mm, at 0us, 60us and 120us respectively. They all indicate the eddy current effect is stronger near the cap. This finding also agrees with our EPI images (Figure6) and localized excitation images (Figure7). Figure6 demonstrates that there are more field distortions in the slice (a) which is closer to the cap than the slice (b). The red solid arrow is the phantom image and dash arrow is the artifacts. Figure 7(a) is the image of surface of the brain and it was titled by the eddy current; the slice (b) is a smooth rectangular image (at the position deeper inside the brain) which shows fewer eddy current. Overall, the simulations provide excellent correlation with the experimental findings.

Conclusions: Eddy current induced by RF coil copper shielding can significantly distort the linear gradient field. These distortions are asymmetric and non-linear at different positions if there is a cap copper shielding. The eddy current simulation method presented in this paper is verified by the measurement results. The agreement of experimental and numerical data demonstrates the potential of using simulation methods in the study of eddy current characterization and in designing methods/techniques that can minimize eddy current.
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References: [1] M. Alecci, et al, MRM, 48: 404-407, 2002; [2] D. Weyers and Q. Liu, US Patent 7102350, 2006, [3] T.S. Ibrahim, et al, ISMRM 2010, #45, [4] H. Zheng, et al, ISMRM 2011 #4440; [5] Van Vaals et al, JMR 90:52-70,1990;[6] P. Jehenson et al, JMR 90: 264-278,1990