Skin effect estimation accuracy in FDTD coil simulations

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Target Audience: Researchers interested in coil sensitivity estimation using the FDTD method.

Purpose: Coil transmit efficiency and noise figure can be estimated using various methods. It has been demonstrated, that unloaded coil Q can be predicted using a simple circuit theoretical approach with an error below 10% by utilizing published loss data for capacitors as well as measured solder loss and analytical expressions for conductor losses [1]. Field simulations are often conducted using the finite-difference time-domain (FDTD) method, which is highly successful in predicting electromagnetic field distributions of MR coils [2], but has difficulties to accurately represent losses in good conductors. The required mesh resolution would, in theory, need to be smaller than the skin depth, thus significantly increasing computational complexity. Several approaches have been proposed to incorporate skin effect losses without lowering resolution [3,4], however their accuracy with respect to the geometries encountered in MR coil simulations has not been established. For strip geometry coils, the dominating loss mechanism at almost all practical frequencies is the lateral skin effect, which cannot be calculated as straightforwardly as the classical skin effect [5], and is not considered in the FDTD good conductor approximations. This work is aimed at investigating the accuracy of FDTD good conductor approximations for wire and strip coils at 128 MHz.

Methods: The simulated coil sizes matched the geometries investigated by Giovannetti et al. [5]. Two 7.5 cm radius coils of equal inductance, one made of 2 mm diameter copper wire, the other of 4.482 mm wide, 40 µm thick copper tape, were simulated using commercial FDTD solvers. Since the estimated losses potentially depend on the actual loss model used and its implementation, we conducted comparable simulations using three commercial FDTD solvers: Remcom XFdtd 7.3 (Remcom, State College, PA, USA), CST MWS 2012 (CST, Darmstadt, Germany) and Speag SEMCAD 14.8 (Speag, Zurich, Switzerland). Coils were surrounded by free space with appropriate boundary conditions, and excited using a 50 Ω voltage source. The copper DC conductivity was taken as 5.8×10^7 S/m. Conformal approximations to model curved surfaces were used where available. To investigate the impact of conformal FDTD on loss estimation, the XFdtd simulations were executed with and without this feature enabled. Steady state port currents and voltages, as well as radiation and copper losses were recorded and subsequently used to calculate the coil resistance terms. Since the mesh resolution is expected to have an influence, all simulations were conducted using three graded meshes with a maximum mesh step of 2 mm, 1 mm and 0.5 mm, respectively, the smallest step being half of these values. The resulting copper resistances were then compared with theoretical expectations. As no closed-form expression for RF conductance of rectangular cross-section conductors is available [6], the strip coil results were compared to the measured results given in [5]. To illustrate the lateral skin modeling accuracy, an additional simulation with a very high resolution of 0.125 mm was conducted in XFdtd.

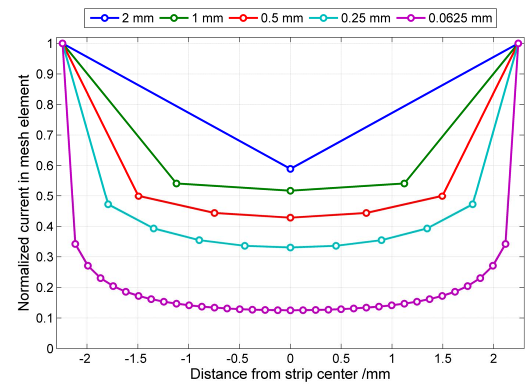

Fig. 1: Current distribution across a strip conductor at different FDTD mesh resolutions. The values are individually normalized to the edge current of the respective simulation. A strong current concentration at the edges is visible, followed by a sharp dropoff towards the next mesh cell.

Results: All simulation results are consolidated in Table 1. The theoretically expected resistance of the wire loop is 0.22 Ω, the additional strip coil lateral skin effect resistance is reported to be a factor 3 higher than the classical wire resistance at 128 MHz based on coil Q measurements [5]. Figure 1 shows the current distribution across the strip conductor for multiple resolutions. High current concentration at the edges is visible, as well as a strong current drop in the nearest neighbors.

Wire coil copper resistance /Ohm

Resolution	MWS	SEMCAD	XFdtd	XFdtdC
2 mm	0.279	0.017	0.288	2.760
1 mm	0.320	0.309	0.318	1.520
0.5 mm	0.337	0.359	0.297	0.494

Strip coil copper resistance /Ohm

Resolution	MWS	SEMCAD	XFdtd	XFdtdC
2 mm	0.181	0.070	0.342	0.178
1 mm	0.221	0.103	0.392	0.227
0.5 mm	0.247	0.144	0.429	0.255

Tab. 1: Copper resistance results for all simulations. There is a strong variation with mesh resolution and between different simulation software packages. Conformal FDTD formulations also have a strong impact on the estimated losses, as can be seen by comparing the XFdtd (default FDTD) and XFdtdC (conformal FDTD) columns.

Discussion: Wire coil results exhibit discrepancies of 26 – 1150 % when compared with the theoretically expected values. Higher mesh resolutions do not necessarily lead to better results, and conformal FDTD formulations potentially have a very strong impact on the loss estimates. Copper strip coils were calculated to have a lower average resistance than wire loops of the same inductance, a strong disagreement with experimental evidence indicating resistances of approximately 0.6 Ω. However, higher mesh resolutions consistently yielded increased resistances, indicating a better representation of lateral skin effect losses.

Conclusion: Metal loss estimates in FDTD displayed a moderate agreement with theory for wire geometries in some cases, but completely failed to predict the increased copper strip resistivity. Due to this result and the irregularities between different mesh sizes and solvers, it is advisable to not rely on FDTD simulation loss estimates. Instead, conductor losses can be implemented as lumped resistances derived from theoretical considerations or measurements of the used conductor geometry. The accuracy of losses in RF coil shields using FDTD simulations needs to be investigated separately.

References:

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