A Comprehensive Coil Resistance Composition Model for High Field

Q. Duan[1], D. K. Sodickson[1], B. Zhang[1], and G. C. Wiggins[1]
[1]Center for Biomedical Imaging, Department of Radiology, NYU School of Medicine, New York, NY, United States

Introduction

Loop coils are still widely-used MR receivers. The resistance of loop coils is an important factor influencing the signal-to-noise ratio (SNR) in the MR experiment. In some applications, such as small loops, low field, or lifted-off coils [1], coil noise could be the dominant factor determining SNR. Thus it is critical to fully understand components contributing in coil resistance for SNR-optimized coil design and electromagnetic field simulation for SNR quantifications [2]. In a recent publication [3], Kumar, *et al*, proposed a coil resistance model composed of resistive loss and effective serial resistances (ESR) of the capacitors and solder joints. The feasibility of this model was demonstrated via Q measurement on small loops for various field strengths. In this abstract, a more comprehensive model is proposed to provide better predictions of coil resistances for large and small loops at high field.

Method

Our current coil resistance model includes following components: conductor loss, radiation loss, ESR of capacitors and soldering joints, and loss in the backing material.

Conductor loss: Conductor loss (or Ohmic loss) characterizes the energy loss in the resistive loop conductors, which can be modeled as $R_{ohm} = \rho \frac{L}{A} = \frac{1}{\sigma}\frac{L}{A}$, with ρ for resistivity and σ for conductivity. At high frequency, skin effect will reduce the effective conducting area. For wire conductor, we have $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$. And thus approximately as shown in [3], $R_{ohm} = \frac{1}{\sigma}\frac{L}{\pi d \delta} = \frac{\sqrt{\pi f \mu \sigma}}{\pi d \sigma} L = \sqrt{\frac{f\mu}{\pi\sigma}}\frac{1}{d} L = \sqrt{\frac{f\mu\rho}{\pi}}\frac{1}{d} L$. This formula is a very good approximation when the skin depth is much smaller than the wire radius. A more accurate model can be found in [4]. Since the conductivity varies with temperature changes, conductor loss is also temperature-dependent.

Radiation loss: Radiation loss characterizes the energy loss via the radiated field of the coil. For loop coil, the radiation loss can be computed by $R_r = 320\pi^4 \left(\frac{\Delta S}{\lambda^2}\right)^2 = \frac{320\pi^4}{\lambda^4}(l_1 * l_2)^2$. Note that the radiation loss is proportional to the 4[th] power of the frequency and the square of the loop area, and does not depend on the temperature at all. Although the existence of coil radiation loss has been well-recognized [5], it was rarely included in the coil resistance models. This was due to the fact that at low field or small coils, radiation losses are negligible in comparison to Ohmic losses. However, as the field strength increases, the contribution of radiation loss to the coil resistance grows exponentially and should not be ignored.

L1(m)	L2(m)
0.1189	0.1067
0.1189	0.1245
0.1338	0.1095
0.1427	0.1443
0.1873	0.1715
0.2676	0.2114

Table. 1: size of test coils

	Ohms
R board per meter	0.1227
R per cap	0.0370
R per solder joint	0.003
R wire per meter	0.4399

Table. 2: coil resistance model parameter for testing coils

ESR of capacitors and soldering joints: Similar to [3], ESR of capacitors can be derived from manufacture's data sheets. Although the ESR of solder joints can be estimated as proposed in [3], it largely depends on the shape and size of each soldering joints. In our model, we just used the average value found in [3].

Loss in the backing material: Almost all coils have to be built on some backing materials to support the structure of the coil element. The most common backing materials include circuit board, PVC board, Teflon, etc. These materials are generally lossy and thus increase the coil resistance. In our model, this component was assumed to be linear with the length of the conductor. To characterize the contribution of the circuit board, two identical coils with and without circuit board were built to compare the coil resistance difference.

Results and Discussions

To validate our model, six rectangular loop elements were built for testing as shown in Table 1. Coils were made of 12awg wire and tuned to 123.2MHz for 3T. All elements except for the largest one have 5 capacitors (largest one has 9). Coil resistance for each test element was measured via unloaded Q factor. Each coil was mounted on G10 circuit board with copper machined off except where pads were needed. In this case, the model parameters were shown in Table 2. Measured coil resistance and corresponding model predicted values are shown in Fig. 1. Unlike Kumar's model [3], coil resistance exhibited strong non-linearity, which is presumably cause by the manifestation of radiation resistance. Predicted coil resistance values by our model, on the other hand, are very close to measured values. This was confirmed by correlation study presented in Fig. 2, with a correlation coefficient of 0.9993 and a p value of 6.5e-7.

An example of coil resistance break down at 3T is shown in Fig. 3 for the 14cm by 14cm test element. The largest component of coil resistance is not the conductor loss (27%), but the radiation losses (38%). This confirms the fact that radiation resistance is no longer negligible at high field for common coil sizes, even though it is still negligible for small coils as presented in [3]. The capacitors take about 17% of the total resistance. The soldering joints and the board losses are 5% and 7% of total resistance, respectively. And for this particular coil element, there is a 6% error in prediction in comparison with measured resistance.

There is still some discrepancy between our predictions to the actual measurements as shown in Fig. 1-3. Besides the possible measurement errors associated with model parameters (e.g. ESR of soldering joints and capacitors) and Q measurement, the non-uniform current distribution for loops at high field could be another possible factor of model underestimations.

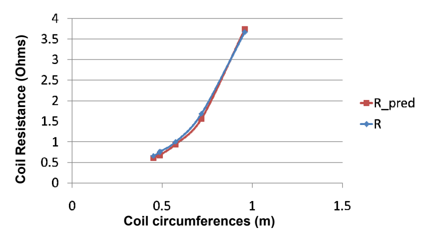

Fig. 1: Measured (blue) and predicted (red) coil resistance.

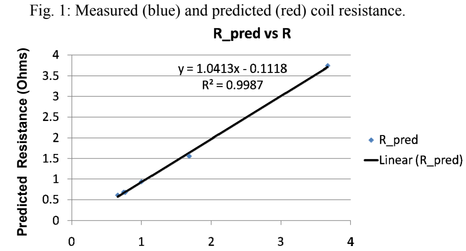

Fig. 2: Correlation of measured and predicted coil resistance.

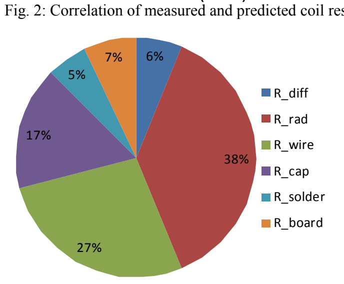

Fig. 3: coil resistance composition of a 14cmx14cm coil at 3T.

Conclusions

This abstract presents a comprehensive model for coil resistance. Compared with existing linear model [3], our model includes radiation loss and backing material loss. The accuracy and feasibility of the model was validated and demonstrated with six coil elements at 3T with extremely good correspondence to measured resistance. It was also shown that radiation resistance is no longer negligible even for a medium size coil at 3T, due to the 4[th] order relationship with frequency and quadratic relationship with coil area. This model can not only provide a guideline in optimizing coil design for SNR, but also could be integrated with full wave simulation for SNR as an accurate coil noise model.

References

[1] Vesselle, et al, IEEE TBME, 42:507-520. [2] Lattanzi, et al, ISMRM 2008: 1074. [3] Kumar, et al, MRM 2009, 61:1201-1209. [4] Al-Asadi, et al. Microwave and Optical Technology Letters, 19(2), 84-87,1998. [5] Vaughan, Ch.6, Ultra High Field Magnetic Resonance Imaging, Springer, 2006