Optimization and sensitivity analysis of Capacitive Inductive and Transformer decoupling schemes for RF coil arrays

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Introduction: Parallel imaging (PI) reduces data acquisition times significantly by acquiring only a portion of the data and reconstructing the full image by incorporating individual coil sensitivity distributions [1]. The quality of images in PI depends, to a great extent, on the g-factor of the coil array, which is directly related to the coil design [2]. Minimizing the coupling between the elements of an array is another critical factor in coil performance; but in most cases, decoupling adjacent elements by partial overlapping might not provide the lowest possible g-factor. Another popular technique using low input impedance preamplifier decoupling [3] can only be used for receive-only RF coil arrays and challenges remain for transmit or transceiver arrays. Other decoupling methods such as transformer, capacitive and inductive decoupling can be used in transmit and receive coils and they may be extended to complex networks for multiple elements [4]. However, to this date no study has been conducted to compare the efficacy of each decoupling method in detail. Physically building the coils and testing each variation would make such work difficult and time consuming. Therefore, using a realistic computer model to simulate RF coil arrays together with detailed decoupling circuitry could be an indispensable tool in determining the most efficient scheme and shortening design process. Such simulations would provide a good starting point for prototyping because one could analyze the performance, sensitivity and tolerances that would closely resemble the real world implementation. In the work presented here, full-wave electromagnetic modeling (HFSS, ANSYS, Canonsburg, PA, US) was used to study and compare the performances of transformer, capacitive and inductive decoupling. We also investigated the sensitivity of decoupling to variations in component values. Such variations might arise from manufacturing tolerances as well as aging or heating, which may degrade the performance of the coil and reduce image quality.

Methods: Individual coil elements were modeled with conductor segments made up of copper foils (width:6.35mm, thickness:0.04mm). Four capacitors of equal values were placed equidistant from each other for tuning. This shortened the electrical lengths of the conductor segments. Then, a single coil element was tuned and matched independently such that the input port reflection coefficient (S11) was below -25dB at f0=127.73MHz (for the transformer decoupling case, one winding of the transformer was also included). The coil was loaded with a two-layer spherical phantom that mimicked the human head. The electrical properties of the inner compartment were selected as the weighted sum of white matter, gray matter and CSF values at f0 (r:8.1cm, σ:0.575/m, loss tan.:1.19, ε:63.40) [5]. For the outer layer, weighted sum of skull’s and scalp’s properties were used (r:8.8cm, σ:0.575/m, loss tan.:0.97, ε:35.860). In the next step, the coil element was replicated and the two coil elements were simulated together without any decoupling circuitry. Resulting coupling between the elements caused the resonance frequencies of the coils to shift and split. The simplified circuit model of two coils with coupling is given in Fig.1. By analyzing the admittance (Y) matrix of the circuit, the coupling factor (m) was found using Eq.1. Here, f1 is the new resonance frequency f1 can be measured from the frequency spectra of the s-parameters and m can be calculated. Using m in Eq.2, required values of C0 or L0 (decoupling elements placed between nodes 1 and 2) can be found for capacitive and inductive decoupling, respectively [6]. The location of the decoupling elements on the coil changes the k value given in Eq.2. For either inductive or capacitive decoupling, the decoupling element L1 or C1 was placed as suggested in [6] and k=1/3. The initial value for the decoupling element C0 or L0 was calculated using Eq.2, but the complete coil array model was simulated while the component’s value was swept from 1/3 to 3 times the initial value. This was done to find the optimal value where the decoupling became maximum (minimum S12). For transformer decoupling, the transformer coil windings were modeled as solenoidal inductors and combined such that the windings combed each other. The placement of transformers is shown in Fig.2. The distance between their axes (d0) was varied to control the amount of mutual coupling, so that it would neutralize the coupling between the two imaging coil elements. Once the optimal values for each decoupling scheme were found, the nominal values were swept by ±40% to investigate the sensitivity of decoupling to variations in element values.

Results: From the single element simulation, the inductance of a single loop was found to be 561nH. In the absence of any decoupling method, the coupling factor m was found as 0.054. Using these measurements in Eq2, the initial values for C0 and L0 were calculated to be 3.65pF and 426nH for the capacitive and inductive decoupling schemes, respectively and d0 was 3.8mm for the transformer decoupling. However, from the simulations where the values were swept, the optimal values were found to be 3.5mm for the transformer and 9.25pF and 280nH, for the capacitive and inductive decoupling, respectively. S12 versus percentage deviation from optimal decoupling value is shown in Figure 3. Sensitivity of S12 to ±5% change in the decoupling component value is given in Table 1.

Conclusions: Full wave electromagnetic modeling is performed for a single coil array to study the performance of transformer, capacitive and inductive decoupling schemes. The sensitivity of decoupling to the variations in values of the components also was analyzed. The results shows that the values calculated for C0 and L0 using the simple circuit model might be a good starting point but a realistic full wave electromagnetic model would be needed to find precise values. In regard to transformer decoupling, the calculated d0 versus the one found in the simulation was in strong agreement because the transformer itself also was modeled within full wave simulation. The results also indicate that inductive decoupling provided the highest decoupling compared to the other techniques. However, capacitive decoupling was the least sensitive to component variability.

Figure 1. Circuit model of two coils.

Figure 2. Transformer decoupled 2 coil elements.

Table 1. S12 vs decoupling element

<table>
<thead>
<tr>
<th>Decoupling</th>
<th>optimum S12</th>
<th>S12 var ±5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>-10.89dB</td>
<td>0.55dB</td>
</tr>
<tr>
<td>Capacitive</td>
<td>-10.63dB</td>
<td>0.23dB</td>
</tr>
<tr>
<td>Inductive</td>
<td>-11.92dB</td>
<td>1.35dB</td>
</tr>
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References: