Investigation of mutual inductance coupling and capacitive decoupling of N-element array system

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Introduction.

In most MRI array designs, optimal coil overlapping is used to minimize coupling between nearest neighbors, while for non-nearest neighbors low input impedance preamplifiers are implemented [1]. However, for some imaging applications, such as partial parallel acquisition (PPA), coil overlap should be avoided in order to make complex sensitivity maps sufficiently distinguished. Furthermore, for cryogenic high-Q arrays [2], geometrical overlap is not practical because it increases the size of each element, thus increasing the ratio of body/coil losses without increasing field of view (FOV). In addition, in order to preserve relatively high Q in cryogenic arrays, the decoupling system should have low loss. A capacitive-only decoupling network seems to fulfill such requirements, however there is limited literature on this subject [3]. In this study therefore, we identified the possible resonant modes in 2x1, 2x2 and 4x1 arrays using an analytical model for an N-element array, and then, knowing the rf modes of each array, we analyzed the mechanism of capacitive decoupling on each.

Method and Results.

A two-state rf current direction model for magnetically coupled coils is developed to analyze possible resonant modes in the N-element array [4]. We considered N-element arrays of linear and circular (with ends coupled) shape. Each resonant mode in the array is related to a different current configuration at each element and is represented by an N x 1 current vector **I** associated with each element, which consists of two-states: ae^{-j0} (clockwise direction, +a state) or $ae^{-j\pi}$ (anti-clockwise direction, -a state). It was assumed that all elements have the same current amplitude a=1, capacitance C_i=C, and self inductance L_i=L. Mutual inductance M_{ij}=M=kL (k is the coupling coefficient, which can be measured at the bench) was considered only for the nearest neighbors (i-j=1). Assuming that one element of the array is in the +1 state (driven element), the current distribution in each other element has two degrees of circulation freedom (+1 or -1), resulting in 2^{N-1} modes in such a system. The number of modes will degenerate to N resonant states for a linear shape or to a smaller number for a circular shape. The voltage V across the capacitance C on each element is related to self-inductance, mutual inductance and current as $\vec{V} = j\omega(\bar{\bar{L}} + \bar{\bar{M}})\vec{I}$. Total electric and magnetic energy at the resonance state of such an array can be expressed accordingly as $W_m = \frac{1}{4}\bar{I}^T \cdot \bar{\bar{L}} \cdot \bar{I}^*$ and $W_e = \frac{1}{4}\bar{V}^T \cdot \bar{\bar{C}} \cdot \bar{V}^*$. Since the total electric and magnetic energies are equal, the resonance frequency of an N-element array can be calculated as $\omega=\omega_0(1\text{-}2kA/N)^{-0.5}$, where A is equal to $\sum_{i=1}^{N-1}(I_i I_{i+1}^* + I_N I_1^*)$ and $\sum_{i=1}^{N-1} I_i I_{i+1}^*$ for circular and linear cases, respectively. Modes with the same summation of A are degenerate at the same frequency. Current amplitudes in each element in a degenerate state are the sum of the amplitudes of all related modes (note in Fig. 1 how the modes are added). Knowing the frequencies and current vectors for all modes of the array (see for example Fig. 1), we can decouple all elements of the array by adding a network of capacitors to the system, therefore shifting individual modes to the same frequency. In such a decoupling technique, the frequencies of all modes are lowered to the frequency of the lowest mode. In this method, the amplitudes of all modes are added and as the result of decoupling, only one element has N units of the current whereas the other N-1 elements will have zero current. In Figs. 2 and 3 examples of such decoupling exercises are presented. Theoretical calculations were confirmed by isolation measurements of 2x1 and 2x2 and 4x1 arrays designed for a 123 MHz Siemens scanner. For the 4x1 array case (not shown here) four resonance modes also were reduced to one, however, due to the lack of full symmetry in such a configuration, a more complicated capacitor network had to be used.

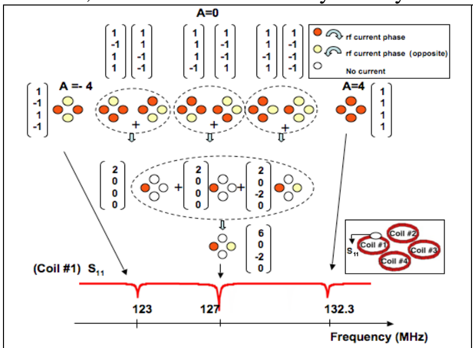

Fig. 1. Three resonant frequencies of a 2x2 array are presented. All 8 possible rf modes are shown together with the related mode current vectors, **I**. Red and yellow circles indicate rf current directions, clockwise and anti-clockwise, respectively; white circle indicates no current. The middle resonant frequency represents six degenerate modes.

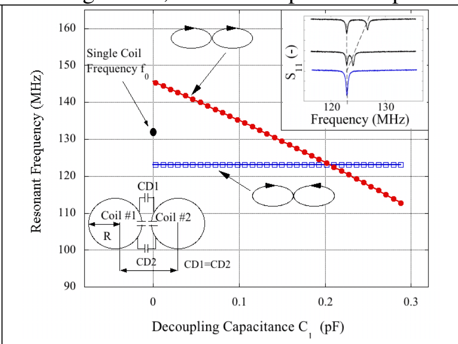

Fig. 2. Calculated frequencies of two modes plotted *vs* decoupling capacitance for a two-element array. Rf current directions for both modes are presented. Inset shows a measured reflection coefficient s_{11} from element #1 for different decupling capacitance CD. Each element was designed for 132 MHz resonant frequency.

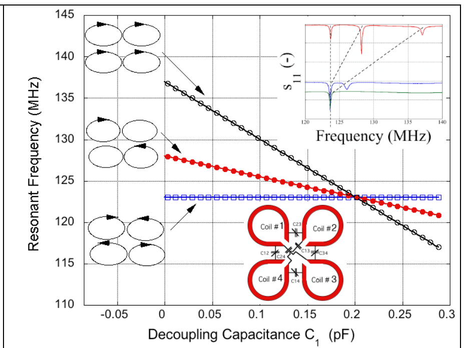

Fig. 3. Calculated frequencies of three modes *vs.* decoupling capacitance (linear combination of CD capacitors) for a 2x2 array. Rf current directions at a given time for three modes are drawn. Inset shows the measured s_{11} from element #1 as a function of frequency for different values of the decoupling capacitance.

Discussion and conclusions

For capacitive decoupling, the decoupled frequency is equal to the lower split frequency, thus for a 2-element array each element has to be designed to resonate at 132 MHz. This is in contrast to the geometrical decoupling case when each single element of the array has to be designed for 123 MHz. Only the symmetric mode is influenced by the decoupling capacitance (Figs. 2 and 3). In the odd mode case, due to the same voltage, there is no *rf* current in the CD capacitors, while in the even mode, when the currents in the elements are in phase, the *rf* current flows in the capacitors thus increasing the capacitance and lowering frequency. For the case of 2x2 and 4x1 arrays, linear combinations of 6 and 8 capacitors were used to achieve element isolation by making all frequency modes of the array degenerate.

Acknowledgements

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