Active Coil Decoupling by Impedance Synthesis using Frequency-Offset Cartesian Feedback

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Introduction Transmit coil arrays are subject to mutual coupling and loading variations, while RF power amplifiers exhibit non-linearity, ill-defined output impedances, and memory effects. To suppress inter-element coupling, current-source techniques exploit transistor output impedances [1-4] but nonlinear output parasitics will degrade their effectiveness. Cartesian feedback (CF) is an alternate approach that senses and linearizes coil current [5]. Frequency Offset Cartesian Feedback (FOCF) [6], avoids DC and quadrature errors of CF, can suppress non-linearity during MR excitation (Fig 1), and can also synthesize arbitrary output impedances when using directional coupler feedback [7]. We propose FOCF impedance synthesis to generate and stabilize the Q-spoil decoupling impedances for transmit coil elements and explore its stability constraints.

Theory In the FOCF impedance synthesis architecture (Fig 2), the directional coupler forward and reverse outputs, V_{fwd} and V_{rev}, are scaled by complex weights, α and β, using vector multipliers [8]. Under high loop-gain conditions, zero reference input and an impressed "reverse" coil signal, the feedback signal is $V_{fb}=\alpha V_{fwd}+\beta V_{rev} = 0$. This forces the effective amplifier output S_{22} to $\Gamma_A = V_{fwd}/V_{rev} = -\beta/\alpha$. Figure 1 shows load-pull measurements of synthesized amplifier impedances $Z_A = Z_o(1+\Gamma_A)/(1-\Gamma_A)$ by adjusting weights α & β. For decoupling, the system output impedance, after being transformed over the feedline coax length, must present a pure reactance mimicking a Q-spoil series inductor that resonates with the coil input shunt capacitor. Conversely, this input capacitor, upon transformation back to the amplifier, presents a decoupling reflection coefficient Γ_c, that for lossy coax, theoretically demands the system create $\Gamma_A = 1/\Gamma_c$. In principle, this implies negative output resistance may be generated, to offset cable attenuation.

Methods FOCF operation was performed on a GE SIGNA 1.5T scanner, with an attached 2-ch PTx system driving two adjacent coils that employ no passive decoupling (Fig 2). Coil 1 is driven directly, while Coil 2 is operated through a FOCF controller, to identical 300W RF amplifiers with output circulators. A vector coupler in the path of power amp #2 provides feedback to the FOCF system. To demonstrate active coil decoupling, we set the ratio and relative angle of feedback terms α and β to produce Z_A that, once transformed, will yield the Q-spoiling impedance at Coil 2. Successful decoupling is checked by transmitting into Coil 1 over 10 power levels while setting the FOCF input to zero, thereby commanding zero current in Coil 2. Using an integral 4-layer PCB coil current sensor, we observed that the coupled currents are indeed attenuated in real-time by 22dB (Fig 3). Moreover, the FOCF-decoupled case yields near-identical MR excitation patterns to the manually disabled (open circuit) case for Coil 2 (Fig 4).

Discussion Even though the RF amplifier is terminated by a circulator, forcing a passive ~50Ω output, FOCF can still synthesize arbitrary impedances by implementing the source absorption theorem [9]. A key issue is system stability with different loads. It can be shown that to synthesize low Z (voltage source), or high Z (current source), the total loop gain/phase depends on the load Z_L. With arbitrary coax lengths, determining a stable median phase is critical. However, if only V_{fwd} is fed back, *and* the power amp uses a circulator or quad-combined pairs, the loop gain and phase is independent of load! The stability sensitivities of FOCF, and real-time feedback methods in general, may present a challenge under wide operating conditions. In these cases, open-loop decoupling, as in Vector Iterative Predistortion [10], remains attractive as the system impedances and linear stability are preset, and thus likely more robust to load changes typical of patient variability.

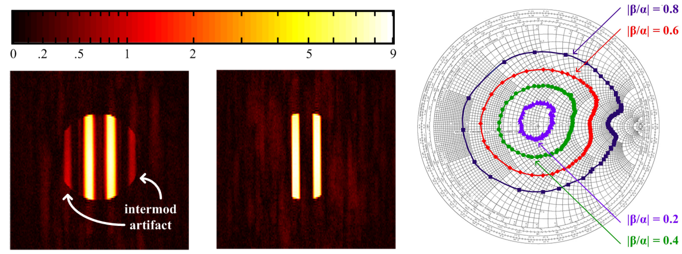

Figure 1: Intermodulation artifacts (left) in a dual band excitation are eliminated by FOCF (middle). FOCF can also synthesize arbitrary output impedance (right).

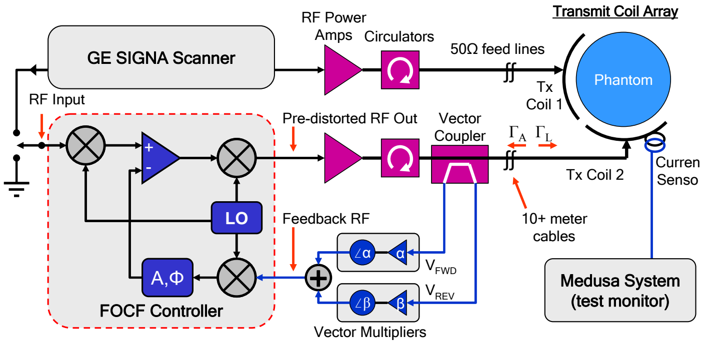

Figure 2: The decoupling experiment employs a standard Tx path for Coil 1, and a FOCF-enabled Tx path for Coil 2. The FOCF system corrects transmit amplitude/phase errors in real-time, and the impedance presented to Tx coil 2 can be controlled by manipulating the feedback weights α and β. A Medusa console and coil current sensor are used only to monitor true coil current for validation.

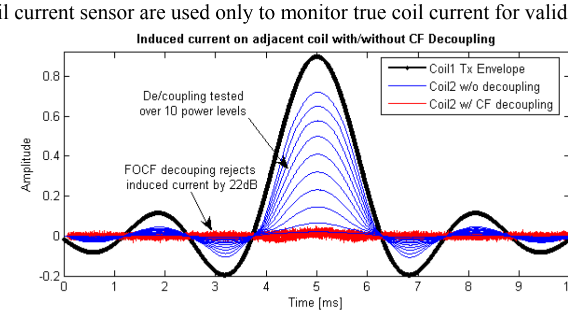

Figure 3: Excitation of Coil 1 induces current in Coil 2. If FOCF is tuned to "Q-spoil" at Coil 2, the coupled current falls by 22dB, providing highly stable active decoupling throughout a 10:1 peak amplitude range.

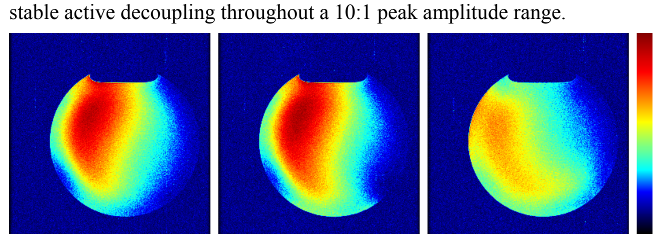

Figure 4: The Coil 1-only excitation pattern (left) is heavily perturbed when Coil 2 is added (right). If Coil 2 is decoupled using FOCF power amplifier impedance control, the single-coil field pattern is restored (middle). Some residual error is expected due to cable losses separating FOCF from the coil.

Conclusions We have successfully demonstrated Cartesian Feedback with MR imaging, providing high-fidelity transmit performance and output impedance control for array decoupling, even without an on-coil sensor. Owing to closed-loop operation, FOCF can adapt near-instantaneously to changing RF amplifier characteristics, impedances, and patient loading producing precision results in spite of disturbances. Yet real-time responsiveness comes at a price: operating conditions can influence stability, a constraint not shared by open-loop methods such as VIP.

References

[1] X. Chu, MRM, 61:952, 2009. [2] K. Kurpad, Concepts MR, 29B:75, 2006. [3] W. Lee, MRM, 62:218 2009. [4] J. Heilman, ISMRM, 16:1097, 2008. [5] D. Hoult, JMR 171:64,2004. [6] M. Zanchi, IEEE MTT,58:1297, 2010. [7] M Zanchi, ISMRM, 18:1465, 2010. [8] G Scott, ISMRM, 14:128, 2006. [9] A.Sedra, K.Smith, Microelectronic Circuits, 1987. [10] P Stang, ISMRM, 17:395, 2009.

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