Frequency Offset Cartesian Feedback Control System for MRI Power Amplifier

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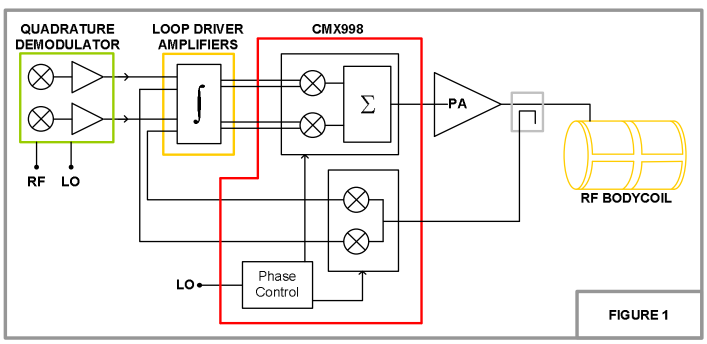
Introduction: As magnetic field strengths continue to increase in human MRI, the RF power and excitation bandwidth also increase, and wavelength effects become significant. Cartesian feedback has been proposed to deal with the rising challenges associated with control over the RF transmission fields [1] [2]. Just like quadrature detection, classic Cartesian feedback can have quadrature excitation ghosts and unmodulated LO leakage, caused by phase or amplitude baseband mismatches and DC offsets. To address these issues, we apply concepts from the architecture of low-IF image-reject receivers [3] to design a modified Cartesian feedback architecture based on complex baseband loop driver amplifiers [4] instead of the classic real baseband amplifiers. This novel architecture controls the RF signal generated by MRI power amplifiers in a range of baseband frequencies offset far away from DC, thus eliminating the effects of baseband mismatches and DC offsets on the MR image quality.

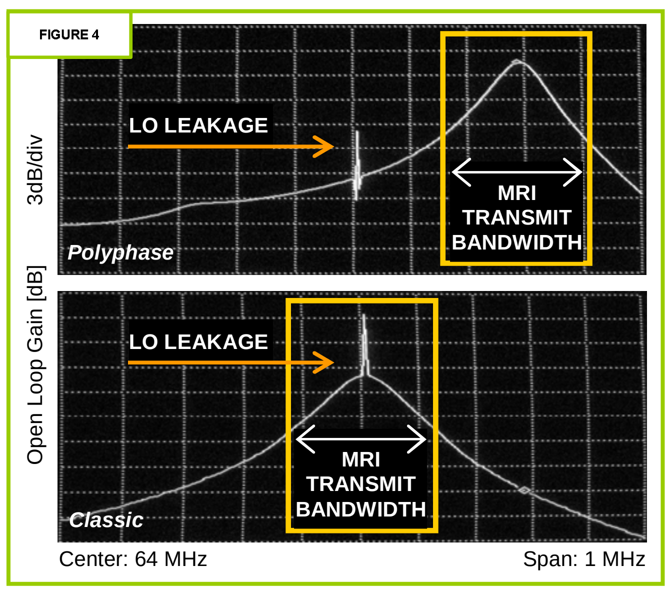
Material Methods: Our goals were to investigate the feasibility of complex-baseband Cartesian feedback control and to demonstrate that the center frequency of the complex baseband can be made high enough for the mirror frequency band and LO frequency to be outside the MRI transmit bandwidth, where they cannot excite quadrature ghosts or LO leakage effects. To meet our goals, we use the newly available CMX998 Cartesian feedback control loop transmitter by CML Microcircuits, which integrates all key functions of the classic Cartesian control loop, including classic error amplification, up/down-conversion, and phase shift control. The CMX998 is specified for RF frequencies over 100 MHz, but we have demonstrated operation down to 40 MHz on the bench. We have also demonstrated a prototype classic Cartesian feedback loop (Figure 1) based on the CMX998 to control the output voltage of a KAA2040 Kalmus power amplifier driving a previously developed birdcage RF test platform near 64 MHz. The feedback signal is the sampled output voltage of the KAA2040. To provide the reference quadrature baseband signals, we built a precision quadrature demodulator driven by an RF source. We then modified the system using active polyphase loop driver amplifiers (Figures 2 and 3) to bypass the CMX998 integrated baseband circuits, thus implementing our first prototype complex-baseband Cartesian feedback loop. The complex baseband center frequency is $\omega_C=(R_C C)^{-1}$, and the half-bandwidth is $\omega_O=(R_F C)^{-1}$. We have analyzed the effect of the finite gain-bandwidth product of the devices implementing the polyphase loop driver amplifiers on the center frequency of the signal frequency band and demonstrated that center frequency shifts over 1 MHz can be obtained with discrete devices, which is enough to move the mirror frequency band outside the bandwidth of most existing MRI transmitters. We have tested both the classic and the complex-baseband Cartesian feedback loop architectures, each in both closed-loop and open-loop configuration, by analyzing the RF signal sensed by a pick-up loop placed inside the RF birdcage.

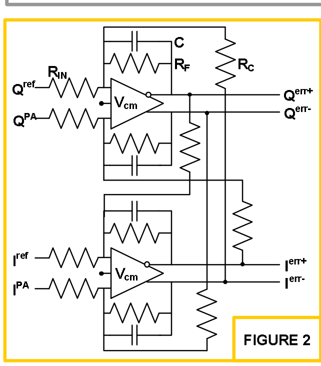
Results: Both the classic and the complex-baseband Cartesian feedback loop architectures, with the integrated CML loop driver amplifiers and the active polyphase loop driver amplifiers respectively, are able to control the output voltage of the Kalmus power amplifier. In the range of baseband frequencies from 20 KHz to 90 KHz, the classic Cartesian feedback loop architecture shows adequate LO rejection (>48 dB, with DC trimming): however, as expected, the matching at baseband and thus the mirror frequency rejection are limited, particularly at the extremes of the control bandwidth, which could cause quadrature ghosts excitations. Our innovative Cartesian feedback loop architecture with polyphase loop driver amplifiers has comparable DC offsets and baseband mismatches as the classic Cartesian architecture, but the MRI transmit control bandwidth is now offset 300 KHz away from the LO frequency, so that these non-idealities cannot excite LO leakage effects or quadrature ghosts. Figure 4 compares the measured open loop gain of the two feedback systems (without DC trimming). LO leakage is apparent but outside the control bandwidth in our architecture.

Conclusion: The classic Cartesian feedback loop architecture has potential quadrature ghosts and LO leakage, caused by baseband mismatches and DC offsets, which create slice-select artifacts. We have designed, built, and validated a prototype complex-baseband Cartesian feedback system to automatically control the output voltage of the power amplifier: it employs active polyphase loop driver amplifiers to shift the control baseband frequencies far away from DC, thus eliminating the effects of phase or amplitude baseband mismatches and DC offsets during MR transmit. While our complex-baseband Cartesian feedback loop controls only the output voltage of the power amplifier, it is conceptually possible to control either the output current or output impedance. In our future work, we intend to investigate both possibilities.

References: [1] D. Hoult *et al*., "The NMR Multi-Transmit phased array," JMR 2004; [2] J. Dawson *et al*., "Feedback Linearization of RF Power Amplifiers," Kluwer Acad. Pub. 2004; [3] P. Abrie, "Design of RF and Microwave Amplifiers and Oscillators," Artech House Pub. 1999; [4] K. Linggajaya *et al*., "A new active polyphase filter for wideband image reject downconverter," Proc. ICSE 2002.







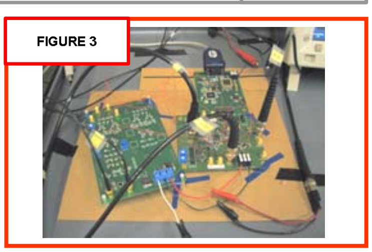


Figure 1: Cartesian feedback power amplifier control system. **Figure 2**: Active polyphase loop driver amplifiers. Without the resistors R_C, it is the classic amplifier architecture. **Figure 3**: Evaluation board with CMX998 loop transmitter (right) interfacing our board hosting the active polyphase amplifiers and the quadrature demodulator (left). **Figure 4**: Open loop gain of the complete control system: with polyphase loop driver amplifiers (top), and with classic amplifiers (bottom).