Non-Magnetic Cartesian Feedback Transceivers – A New Approach to MR RF Instrumentation

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Introduction

The Cartesian feedback (CF) method of MR transmitter and receiver operation confers numerous advantages in both spectroscopy and imaging[1]: *Transmission:* effective decoupling (~ x100) of coil arrays while maintaining optimal RF power utilisation; knowledge of amplitude *and phase* of coil coupling constants; 100-fold reduction of phase/amplitude distortion caused by signal chain non-linearity (see Fig. 1), thereby admitting cheap, efficient, class-AB power amplifiers; constant probe B_1 field regardless of significant changes in tuning, loading and matching; simple warning of transmitter saturation caused by phased-array coupling voltages.

Reception: > 100-fold reduction of phase modulation caused by probe vibration; > 100-fold reduction of "radiation" damping; absolute receiver calibration – the signal strength for a given flip angle remains constant regardless of significant changes in probe tuning, etc.; > x 100 decoupling of coil arrays while maintaining optimal S/N ratio.

When decoupling phased array coils during transmission, it is essential to maintain a high current blocking factor over the full bandwidth Δω of the shortest pulse likely to be encountered – e.g. 20 kHz. However, our prototype CF instrument[1] gave full bandwidth blocking over only 2 kHz. This limitation was mostly due to the long cable lengths between the probe and the instrument, which perforce was in a low magnetic field. This limitation will worsen with increased B_0 field strength. In addition, significant RF power is lost in long cables, and cross-talk among the multiple long cables between array coils and spectrometers has been noted[2]. We therefore report here the successful construction of balanced CF transceivers and power amplifiers (plus digital control systems) with Δω ~ 20 kHz *that can function in the strong magnetic field around the magnet bore entrance*. This radical concept is shown in Fig. 2.

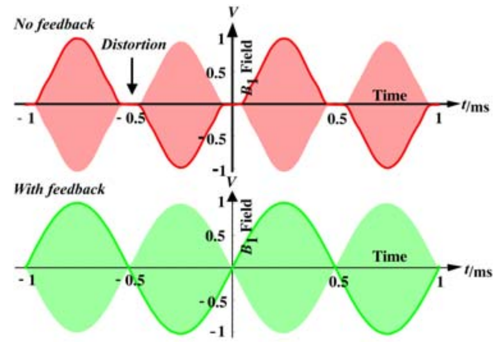

Figure 1. Correction of RF amplifier chain distortion by Cartesian feedback. (From oscilloscope recordings.)

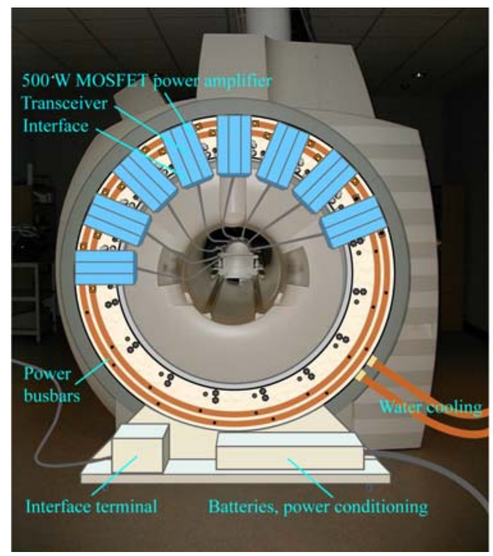

Figure 2. Artist's conception of the mounting of CF transceivers and power amplifiers behind the magnet.

A First Production Model

The transceiver functions from 10 to 1000 MHz to accommodate all Larmor frequencies for the foreseeable future, has a probe-dependent *signal* bandwidth of at least 2 MHz, is digitally controlled, and is designed to function as part of an ensemble, as shown. A balanced electrical construction was used throughout to minimise any problems caused by the absence of ferrites; some of the novel circuitry required was described in a previous ISMRM Conference[3]. In researching a balanced, broadband, liquid-cooled 500 W MOSFET power amplifier, optimal power loading was thoroughly investigated. By direct resonant frequency and Q-factor measurements with an *inductive* load, it was found that the ratio of the output resistance to the optimal load resistance was only 7.6 at low power; it diminished at higher powers. Thus with coupled coils, the maximum blocking of induced current the amplifier can provide without Cartesian feedback is only 18.7 dB, not 40 dB. An earlier indirect measurement by the authors with a single-ended, commercial, 300 W MOSFET amplifier gave a maximum blocking factor of 16 dB.

The instrument has been tested in fields of up to 1.3 T, a typical bore-end field strength, and a signal bandwidth ~ 5 MHz (the probe's limiting contribution is omitted here) has been attained. Thus, with a loaded probe coil, full (x 100) bandwidth blocking was achieved over the desired bandwidth Δω of 20 kHz, as shown in Fig. 3. It is noteworthy that this was accomplished with a phantom and two coupled surface coils, *both of which were attached to a CF transceiver*. Both transceivers appeared to be totally stable, even when the inductive coupling between the two coils was deliberately made large.

The transceivers are completely digitally controlled by a computer remote from the magnet. Control and signal intake have been achieved with a novel machine control software language and a ferrite-free Universal Serial Bus (USB)-based system that can propagate data via only two coaxial cables at a rate of 40 Mbytes per second. It employs well-known system architectures combined in a novel fashion.

Non-magnetic batteries have been investigated for power supplies and their use is eminently feasible. As the duty cycle of RF power amplifiers in MRI is low, trickle-charging is the preferred means of maintaining their power.

Interfacing to a commercial instrument presents severe challenges. Commercial transceivers are uniformly digital, dispensing with baseband (audio frequency) pulses, free induction decays and echoes. Typically, pulses and echoes are digitised in a modulated fashion. (A crude example would be that alternate sample points every 100 ns are inverted to give a modulated 5 MHz square wave.) In contrast, because negative feedback is used, CF transceivers are traditional (albeit "hi-tech") in design: they demand in transmission electrical analogue voltages that are direct representations of the real and imaginary parts of pulses (e.g. a hyperbolic secant pulse) while in reception they yield analogue quadrature voltages that are direct representations of the *x-y* magnetisation in the rotating frame. Solutions we are investigating include: demodulating the commercial pulse and modulating the CF receiver quadrature outputs so that they mimic the commercial signals; building our own pulse programmer and digital signal processing boards that present the commercial computer with raw spectra or images; working with a manufacturer to provide and accept baseband signals.

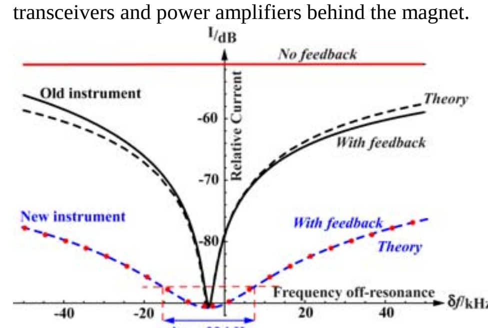

Figure 3. The 100-fold reduction by Cartesian feedback of induced current in a coupled array coil.

Conclusion

A radical decision to place MR CF transceivers close to the magnet has been implemented. Multiple, *non-magnetic* Cartesian feedback technology is viable and ultimately, a CF system may be cheaper than a traditional instrument – in part because no great care needs to be taken over amplifier distortion, as shown in Fig. 1. Generating broadband RF power with MOSFET transistors without ferrites is eminently feasible; it may be shown that the blocking factor they give enhances that due to feedback – the same is true of pre-amplifiers in signal reception. Finally, digital control in a strong magnetic field is also possible.

References

1. D. I. Hoult *et al*, J. Magn. Reson. **171**, 57–63 and 64–70, 2004**. 2**. G. Scott & K. Yu, Proc. Intl. Soc. Mag. Reson. Med. **13**, 330, 2005. **3.** *D. I. Hoult, et al*, Proc. Intl. Soc. Mag. Reson. Med. **14**, 2202, 2006.