A 'Hi-Fi' Cartesian Feedback Spectrometer for Precise Quantitation and Superior Performance

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Introduction

There are numerous defects and deficiencies of magnetic resonance instrumentation to which the user becomes first resigned then oblivious. Chief is that a spectrometer or imager is uncalibrated in an absolute manner. Thus when transmitting, a change in or of the sample (e.g. non-conducting to conducting, polar to non-polar, etc.) often necessitates a change of pulse power or length – even if the probe has been re-tuned and re-matched. Concomitantly, upon reception, even if different samples contain the same number of nuclei, the amplitudes of their free induction decays following a 90^{o} pulse (i.e. the integrals of the spectra) may differ. With an ideal instrument, such changes would not occur. The user would dictate the pulse type, its flip-angle and bandwidth or duration, and the settings would then remain fixed regardless of the sample. Equally, for constant sample temperature, the amplitude of the FID would depend solely on the receiver gain and the number of nuclei, once again regardless of sample composition – only the noise would vary from sample to sample. Thus, taking two examples among many, there would be no need to worry that the swelling of a perfused heart would change the pulse length and 31P signal strength, or that the breathing of a patient in an imaging experiment would do likewise.

These shortcomings are caused by the tuned and matched probe, for its Q-factor and tuning are dependent on its environment; in particular, both variables are sample-dependent. A further related defect is that tuning can be modulated by movement and vibration (e.g. sample spinning, field gradient acoustic noise, etc.), causing extra "1/*f*" noise and sidebands about a resonance and "*t*1" noise in two dimensional spectra via phase modulation. Further diverse annoyances include radiation damping, and pulse amplitude and phase distortion due to transmitter power supply "droop" (heating of transistors) and crossed diode, or even PIN diode, T/R switches. Such distortion particularly affects shaped pulses and may degrade applications as diverse as water suppression and image slice profile. Finally, interactions between elements of a crossed-coil (quadrature) probe or phased-array system (a separate submission) can seriously degrade their use during transmission and also, without low input-impedance pre-amplifiers, their application during reception.

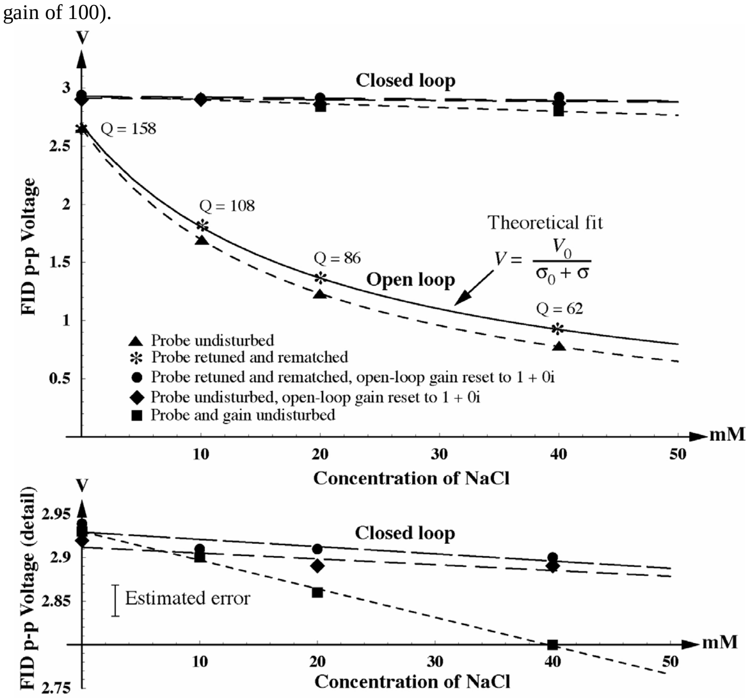
A Cartesian Feedback "Cure-all"

Electronic negative feedback appears potentially to be a cure for *all* these ills. For example, during transmission (the easier mode to understand), we could monitor the probe B_1 field with a small sense loop and with the aid of the spectrometer's receiver, compare it with the applied voltage at the transmitter modulator input, then correct any error by using Black's classic negative feedback arrangement. Thus with this idea, both transmitter and receiver are always on. However, feedback in a radio frequency context is difficult, thanks to the rapid change of phase with frequency of the average spectrometer (excessive group delay) and oscillation inevitably results. The solution is deliberately to restrict the bandwidth of the instrument (e.g. to 2 kHz with no feedback applied) so that a single-pole filter dominates the response of the putative feedback loop. However, this requires an RF filter with an impossibly large Q-factor. A full four-quadrant solution to this problem was proposed by Chen and Hoult 15 years ago (1), following earlier (single quadrant) work on shaping Gaussian pulses by Hutchison *et al.* (2); further, the solution's efficacy in removing radiation damping was demonstrated in 1995 by Broekaert and Jeener (3). This solution involves applying filters in the *audio* frequency sections of a conventional analogue instrument and performing the needed comparison there, in quadrature phase, before feeding the difference back through the transmitter, a technique now known in the communications industry as "Cartesian feedback" (4). Upon closing the feedback loop, the bandwidth opens up again to a useful value by a factor equal to the open loop gain (e.g. from 2 kHz to 200 kHz with an open-loop gain of 100).

During signal reception, it can be shown that the feedback mechanism effectively places a high impedance pre-amplifier in series with the probe coil (c.f. pre-amplifier damping) and thus eliminates dependence on probe tuning and matching. We thus report a successful outcome where both the transmitter and receiver of a 128 MHz prototype spectrometer operate in feedback mode, and all the benefits listed above appear to have been obtained. We have encountered no instability and the electronics appears to function as predicted. Ongoing research is aimed at reducing the group delay round the feedback loop so as to increase the bandwidth over which the full benefits of the feedback are obtained.

Implications

It is no exaggeration to state that this novel, albeit difficult, technique has the potential to alter completely the way in which the MR spectrometer or imager is used, controlled and programmed. It is a Pandora's box that we are just beginning to explore, as more and more possibilities for automatic set-up and calibration of the instrument become apparent.



The beneficial effects of feedback on the signal strength from a sample of varying conductivity σ. Open-loop gains are relative to a base of x100.

References

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