Hybrid Digital Phase-Locked Loop and Moving Average Filtering Improves SNR in Spatio-Temporal Field Monitoring

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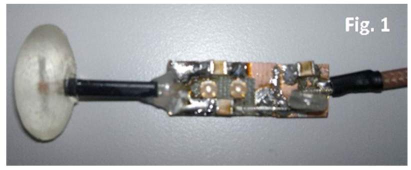
Introduction: B0 field monitoring using NMR probes has been used in a number of applications such as artefact correction for image reconstruction, gradient and shim system characterisation and real-time field updating [1-2]. Since the probes are small for high spatial resolution and specificity, the signal is relatively noisy. Furthermore the magnetic field, which is usually described using spherical harmonics, is obtained from the derivative of the phases of the FIDs [3]. If a conventional finite-difference algorithm is used to calculate the derivative then the noise will be further amplified [4]. The resulting low SNR of the B0 field measurements restrict temporal resolution and readout times of the approach. However, faster update rates in closed-loop control of the B0 field stability, detection of small B0 fluctuations in phase contrast on spectroscopy measurements and monitoring of long read-out trains is desired, calling for more SNR/time in spatio-temporal field monitoring.



So far processing was based on smoothing (moving average) filters applied to the field coefficients [5]. However we can also take advantage of the FID signal because even if the SNR of the FID is still sufficient, there can be phase jitter which would lead to enhanced noise in the phase and finally field coefficients. Since the phase needs to be preserved any zero-phase filter can be used but the phase-lock loop (PLL) – which attempts to keep real and imaginary parts of the FID in phase – was investigated [6] here to improve SNR in spatio-temporal field monitoring.

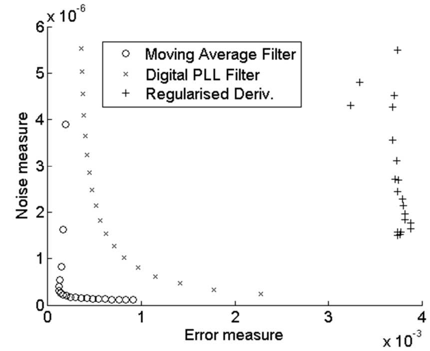


Fig. 2: Comparison of different filtering methods. The error measure is the integral error where the error is the difference between the predicted response and the actual response during transients (gradient ramp up/down). The noise measure is the integral square error when no gradients are applied.

Method: A NMR field probe similar to the one described in [2] was constructed (fig. 1). The probe was susceptibility matched to copper and the water samples were doped with CuSO4 reducing the T1 and T2 to approximately 80ms. The probe was tuned to the B0 frequency of 400MHz, matched to 50 Ω and operated in transmit/receive mode. A rectangular RF excitation pulse of 0.5ms duration was used. The measurements were performed on a 9.4T Siemens Magnetom scanner (Erlangen, Germany) with a sampling rate of 300kHz. For testing purposes, a gradient in the x-direction was switched on and off to produce a triangular wave-form. The gradient amplitude was 5mT/m and the slew rate was 40mT/m/ms.

A second-order digital PLL filter is used rather than an analogue filter so that any phase noise induced during the data acquisition can also be filtered. Although this filter does not remove phase offsets, this is not a problem since the derivative of the phase coefficients is used (i.e. the field coefficients). The closed-loop poles were constrained to be real and equal to give a closed-loop response that has no oscillation and is as fast as possible. The closed-loop transfer function of this filter in the z-domain, and the constraint, is:

$$H(z) = \frac{\gamma((1+\rho)z-1)}{z^2+(\gamma+\gamma\rho-2)z+(1-\gamma)}, \qquad \gamma = \frac{4\rho}{(1+\rho)^2}$$

Three filtering methods are compared: the moving average filter, the digital PLL filter and regularised derivative [4]. The moving average filters the field coefficients (after differentiation) while the digital PLL filters the phase coefficients (before differentiation). The last method filters the noise during the differentiation process. The first two filters use the finite difference to calculate the derivative of the phase.

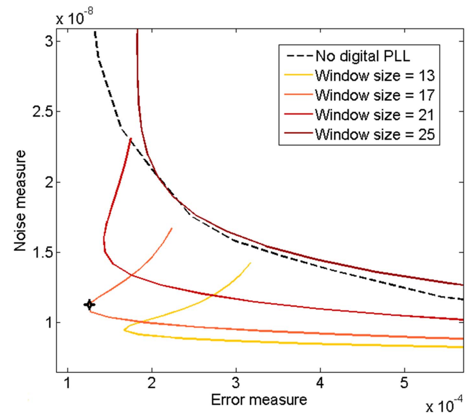


Fig. 3: Comparison of the performance of the digital PLL with a moving average filter. Different bandwidths for the digital PLL filter were used (between 200 and 800 times greater than the bandwidth of the gradient system). The performance of only a moving average filter with a range of window sizes is shown as a reference.

Results: There are two objectives that we need to achieve when filtering data: firstly, the noise needs to be reduced and secondly we want to preserve the underlying signal as much as possible without over-smoothing it with the filter.

Fig. 2 shows the moving average window size 3 to 41; the digital PLL with γ from 200 to 800 times the gradient system bandwith; the regularisation numerical differentiation algorithm with regularisation term α from 5e3 to 32e4. The digital PLL was found to outperform the regularised numerical derivative but the moving-average still outperforms the PLL. However, fig. 3 shows that a combination of the moving average filter and the digital PLL filter is better than a moving average filter alone. The optimal parameters were moving average with window size 17 and PLL with bandwidth 360 times greater than the gradient system's bandwidth.

The time-domain results of the filters are compared in fig. 4. The PLL filter alone is relatively noisy and introduces artificial overshoots while the moving-average and hybrid filters greatly improve the SNR. The predicted response was calculated using gradient system characterization methods similar to [3].

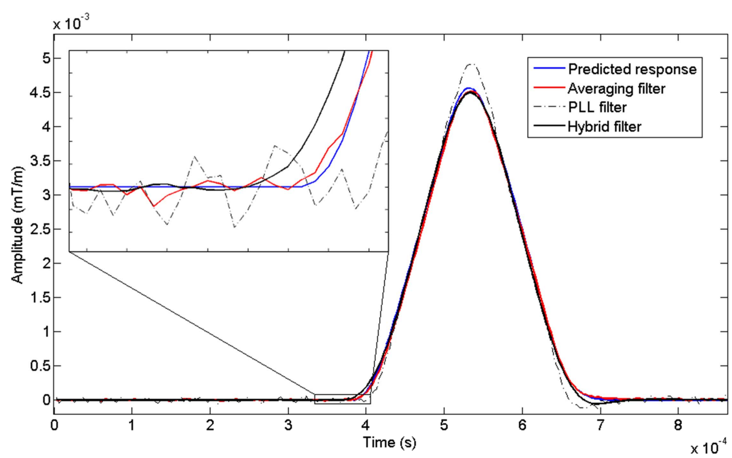


Fig.4: Time domain plots of derivative of the phase signals using different filters. The moving average filter's window size is 13. The PLL filter bandwidth is 360 times higher than the gradient system bandwidth. The hybrid filter is the same as the PLL filter but also with an averaging filter with a window size of 17.

Conclusion: It was shown that the averaging filter is still the best filter for reducing noise and preserving the underlying signal. However, it can be further improved by using it in combination with a digital PLL filter. The digital PLL filter requires additional computation time but because it is an infinite impulse response filter, the computation is simply a difference equation which can be applied in real-time during data acquisition.

For future research, different design criteria for the digital PLL filter can be investigated or even different types of zero-phase filters.

References

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