Journal of Magnetic Resonance 220 (2012) 26–31

Contents lists available at SciVerse ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

Continuous SWIFT

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ARTICLE INFO

Article history:
Received 2 September 2011
Revised 25 April 2012
Available online 9 May 2012

Keywords:
MRI
Spectroscopy
Continuous wave
Sweep Imaging
SWIFT

ABSTRACT

This work describes our first efforts to implement SWIFT (SWeep Imaging with Fourier Transformation) in continuous mode for imaging and spectroscopy. We connected a standard quadrature hybrid with a quad coil and acquired NMR signal during continuous radiofrequency excitation. We utilized a chirped radiofrequency pulse to minimize the instantaneous radiofrequency field during excitation of the spin system for the target flip angle and bandwidth. Due to the complete absence of "dead time", continuous SWIFT has the potential to extend applications of MRI and spectroscopy in studies of spin systems having extremely fast relaxation or broad chemical shift distributions beyond the range of existing MRI sequences.

1. Introduction

In the late 1970s, manufacturers of NMR instruments changed direction from producing continuous wave (CW) spectrometers to pulsed Fourier Transformation (FT) spectrometers. The change was enabled by extensive computerization of spectrometers and the development of the FFT [1], and was predominantly motivated by Ernst's work [2–5] showing the advantages of pulsed FT techniques for spectroscopy. Acquisition in the presence of a radiofrequency (RF) field of very low power (milliwatts) was replaced by acquisition of a free induction decay (FID) following a short (microseconds) RF excitation pulse of high power (kilowatts). Frequency and field modulation with lock-in receivers became obsolete and creative efforts were instead directed toward improvement of high power transmitters, fast transmit/receive (T/R) switches, and flexible pulse programmers. Modern magnetic resonance imaging (MRI) was developed based on the same pulsed FT NMR platform [6]. However, due to the need to use larger probes in most MRI applications, the requirements for MRI scanners are different from the requirements for NMR spectroscopy. Larger RF coils in MRI demand higher power and require longer pulse lengths to excite the spin system to the same flip angle. Indeed, acquiring an FID after a long RF pulse no longer yields a high quality (baseline free) spectrum of the spin system. In reality the acquired signal is a truncated FID with inevitable off-resonance phase distortion and decreased contribution from fast relaxing spins. Therefore, MRI more than NMR spectroscopy can gain from using elements of the "old" CW, rapid scan [7], and stochastic [8] techniques. One example of reviving ideas from CW NMR is the use of adiabatic pulses [9–11] in many MRI applications. Another example is the SWIFT method (SWeep Imaging with Fourier Transformation) [12], which uses swept RF excitation and virtually simultaneous signal acquisition in a time-shared mode. SWIFT has significant benefits for studying objects with ultra-fast spin-spin relaxation rates and has already found many applications [13–16]. In the time-shared mode, the transmitter is "on" during time τ_p and "off" during the rest of the dwell time $d_w = 1/b_w$ for the acquisition, where b_w is the baseband excitation bandwidth and $d_c = \tau_p b_w$ is a transmitter's duty cycle. In this "gapped" mode of SWIFT, the RF excitation energy is proportional to the ratio $\frac{b_w}{d_c}$ [17]. Gapping always compromises the signal-to-noise ratio (S/N) compared to un-gapped acquisition because $S/N \propto \sqrt{1 - d_c - t_d\, b_w}$, where t_d is "dead time". The dead time is the time period after switching the transmitter off, during which the decaying residual transmitter signal is higher than the thermal noise background, which prevents acquisition. For a standard T/R switched transceive coil, t_d is proportional to the coil ring-down time, which depends on the quality factor Q of the coil and the Larmor frequency as $\frac{Q}{\omega_0}$ [18]. Due to this constraint, very high excitation bandwidths can be difficult to achieve with gapped SWIFT especially at low Larmor frequencies due to the finite t_d required for ring-down. Furthermore, t_d consumes valuable acquisition time in the gaps. Thus, time-shared acquisition imposes a practical limitation for the SWIFT technique. However time-shared acquisition is just one of many modulation techniques used in CW spectroscopy to isolate spin signal from the excitation field [19,20] that can be considered for SWIFT. A continuous wave NMR imaging (CW-NMRI) system, which utilized

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http://dx.doi.org/10.1016/j.jmr.2012.04.016

magnetic field modulation in the slow sweep condition together with phase-sensitive detection and lock-in amplifier, has been demonstrated for three-dimensional multi-nuclear imaging of different materials [21]. In addition, a sideband modulation technique adapted to a modern scanner using a digital receiver was proposed recently [22,23]. There are also different schemes with hybrids and circulators used in radar technology to reach considerable T/R isolation [24]. The goal of the present work is to implement SWIFT in a continuous mode (cSWIFT) for imaging and spectroscopy on a modern MRI scanner with minimal hardware modification. We describe below our initial results and discuss possible future improvements.

2. Theory

2.1. Signal description

A sweeping frequency can be written as an explicit function of both time and frequency. The response to such excitation can be treated in either the time or frequency domain. In the case of constant RF amplitude and linear frequency sweep, the pulse is represented by the chirp function [25]:

$$c^- = \exp(-i\pi bt^2) = \exp(-i\omega^2/4\pi b)$$
$$c^+ = \exp(i\pi bt^2) = \exp(i\omega^2/4\pi b) \quad (1)$$

where b is the sweep rate in s^{-2} and the subscript "−" or "+" denotes the sign of the frequency sweep direction. In continuous mode the acquired raw signal, S, consists of the mixture of the spin signal with the "leakage" of the transmitted signal. For small flip angles, when the spin system can be considered a linear system, the spin signal presents as the convolution of the FID, $h(t)$, with the excitation function [26]. Thus S is described as:

$$S = (h(t) \oplus c^+)c^- + Ae^{i\varphi} \quad (2)$$

where the symbol $\oplus$ means convolution, multiplication by c^- describes phase sensitive detection with the receiver frequency locked to the excitation frequency (the frequency-modulated (FM) frame [9]), and where A and φ are the relative amplitude and phase of the transmitter leakage signal. In the FM frame, the transmitter signal is a smooth function of time and may be subtracted using some type of model-based fit (see below). Afterwards, the spectrum of the spins, $H(\omega)$, can be extracted by one of the existing schemes of deconvolution (correlation) by considering: (a) the signal in the time domain as in the SWIFT method:

$$H(\omega) = \mathrm{F}\{h(t) \oplus c^+\} * \mathrm{F}\{c^+\} \quad (3)$$

or (b) as a frequency domain signal, as used in the rapid scan correlation method [7,27]:

$$H(\omega) = \mathrm{F}\{\mathrm{F}^-\{(h(t) \oplus c^+)c^-\}c^-\} \quad (4)$$

where the operation F{} represents Fourier transformation. In practice however, baseline correction is incapable of fully removing the transmitter leakage signal. One can show that due to pulse non-ideality and boundary effects the residual transmitter signal will be transformed differently in these two specific de-convolution procedures, which could be used as a quality test of the baseline correction. A combination of the results might be used as an additional tool to clean up the resulting spectrum.

2.2. Levels of spin signals and leakage

The amplitude of the frequency-modulated pulse in frequency units, ω_1 , that is needed to excite a spin system with flip angle, θ, and bandwidth, b_w, satisfies the relation [17]:

$$\omega_1 = \gamma B_1 \approx \beta^{1/2n}\theta b_w / d_c\sqrt{R} \quad (5)$$

where γ is the gyromagnetic ratio, B_1 is the RF field amplitude, $\beta^{1/2n}$ is a shape function (which is equal to 1 for a chirp pulse), T_p is the pulse length, and $R = T_p b_w$. The curves in Fig. 1 present the calculated values of ω_1 needed to rotate a proton spin system to the "Ernst angle" in a spoiled steady-state experiment with longitudinal relaxation time T_1 = 1 s. The repetition time, T_R, is equal to the acquisition time, which in the case of SWIFT is equal to T_p. In the case of gapped SWIFT, the hyperbolic secant (HS) shape with transmitter duty cycle d_c = 0.33 with R = 256 was used. For comparison, the RF amplitude needed for a standard square hard pulse having length equal to $1/(3 * b_w)$ [17] is also presented. Note that cSWIFT, in comparison to pulsed MRI, needs about 100 times (40db) lower amplitude of the RF pulse or less, depending on R value.

To obtain a rough estimate of the relative levels of the RF amplitude in comparison to the spin signal amplitude during a gapped SWIFT experiment (with HS pulse, d_c = 0.33, R = 256, b_w = 60 kHz), we first performed direct measurements with an oscilloscope. A 15-cm spherical phantom filled with water was used. The voltage scale shown in Fig. 1 was set based on those measurements. We also estimated that the receiver threshold was about 1.3 V with these parameters. The receiver threshold was the maximum signal level allowed as determined by the electronic sensor in the Agilent system which gives the "overflow" error message when it is exceeded. Thus, according Fig. 1, to ensure that, with the utilized parameter set, a signal in continuous mode does not exceed the specified linear region of the receiver, a minimum of 40 db isolation between the transmitter and receiver is required.

2.3. Transmitter–receiver isolation

To reduce the dynamic range of the signal and to decrease the contribution of the transmitter's systematic and thermal noise in the resulting spectra, the leakage amplitude A must be minimized. Let's consider a well-known scheme in MRI based on a quadrature hybrid used to connect quad coils (Fig. 2). This connection scheme is also in use for monostatic radar as a self-duplexer with about 30–40 db T/R isolation [24].

The leakage A in this scheme has at least two sources. The first, A_{hh}, is due to direct coupling between transmitter and receiver via connectors inside the hybrid, which depends on the quality of the hybrid. The second, A_{ch}, appears due to a mismatch of impedances between the coil probe and hybrid. Considering that the hybrid's bandwidth is much broader than that of the coil, one can conclude that the frequency dependence of the leakage is mostly determined

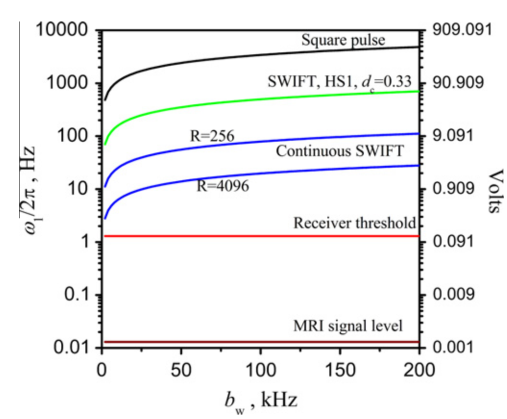

Fig. 1. The calculated values of ω_1 (left axis) and estimated voltages (right axis) of RF amplitude vs. bandwidth in comparison with the amplitude of the spin signal and receiver threshold (details in the text).