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A Novel Digital Magnetic Resonance Imaging Spectrometer

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Abstract—**Spectrometer is the essential part of magnetic resonance imaging (MRI) system. It controls the transmitting and receiving of signals. Many commercial spectrometers are now available. However, they are usually costly and complex. In this paper, a new digital spectrometer based on PCI extensions for instrumentation (PXI) architecture is presented. Radio frequency (RF) pulse is generated with the method of digital synthesis and its frequency and phase are continuously tunable. MR signal acquired by receiver coils is processed by digital quadrature detection and filtered to get the k-space data, which avoid the spectral distortion due to amplitude and phase errors between two channels of traditional detection. Compared to the conventional design, the presented spectrometer is built with general PXI platform and boards. This design works in a digital manner with features of low cost, high performance and accuracy. The experiments demonstrate its efficiency.**

Keywords—**spectrometer, magnetic resonance imaging, PXI platform, digital quadrature detection**

I. INTRODUCTION

MRI is now one of the most important tools in medical diagnostics with features such as high resolution, non-invasive and arbitrary slice imaging, etc. It has been widely used for *in-vivo* studies [1], [2].

As the essential part of MRI system, spectrometer controls the transmitting and receiving of signals [3]. Varies of designs have been presented over the last 20 years or so [4], [5]. With the development of computer technology, electronic technology, data processing and so on, many new techniques are applied in spectrometer. For example, direct digital synthesis (DDS) has been used to generate RF pulse [6], [7]. MR signal was processed with synchronous homodyne detection [8]. Programmable pulse generator has also been proposed [9]. However, these recently developed powerful spectrometers are usually expensive, complex and inflexible.

In this paper, we propose a new digital spectrometer based on PXI platform, which is designed with the general PXI platform and boards. Firstly, the time sequence is quantified according to the MRI scan sequence. At the same time, digital RF pulse and gradient pulse are calculated. Secondly, the timer board generates trigger signals in terms of time sequence to trigger DAC boards, and the digital RF pulse and gradient pulse are converted to analog signal. After imaging objects resonance, MR signal is digitized and processed with digital quadrature detection. Finally, we obtain the k-space data used to imaging after digital filtering.

Compared with traditional spectrometer, the proposed design is able to achieve high performance and accuracy with low cost. Moreover, digital generation of RF pulse makes it easy to switch the phase and frequency continuously. Application of digital quadrature detection avoids the spectral distortion, which could occur by using conventional detection method, due to amplitude and phase errors between two channels.

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II. METHODOLOGY

A. Theories and Architecture

The block diagram of our spectrometer is displayed in Fig.1. It is composed of five parts, system controller, pulse controller, RF transmitter, RF receiver and gradient generator. System controller deals with the compilation of scan sequence, calculation of digital waveform and data processing. Pulse controller sends trigger signals to other modules to manage the time sequence. RF transmitter and gradient generator produce the RF pulse and gradient pulse. RF receiver acquires and processes MR signals.

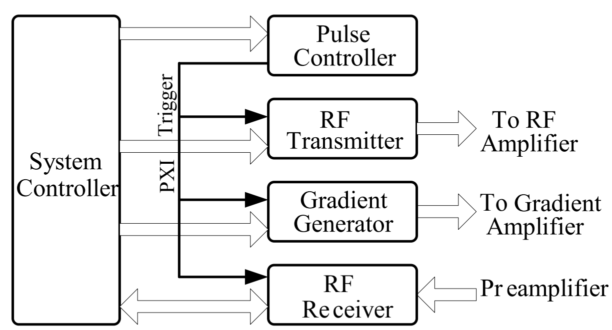

Fig. 1. Block diagram of spectrometer

The spectrometer is based on PXI platform. PXI is an open industry standard created by PXI System Alliance. It inherits the electrical features defined by peripheral component interconnect (PCI) specification and form factors of CompactPCI. The PXI specification adds electrical features to meet the high-performance requirements by providing system clock, trigger bus, local bus and star trigger [10]. The system clock of PXI platform is used as reference clock of phase-lock loop (PLL) to synchronize all modules, and PXI trigger bus is used to transmit the trigger pulse in our system.

The system controller is actually an on-board computer. It compiles the MRI scan sequence and calculates the time sequences of all modules. Digital RF waveform and gradient waveform are also calculated. Then the pulse controller is set to generate trigger signals in terms of time sequence. The signals are emitted from PXI trigger buses to trigger RF transmitter and gradient generator. Digital RF waveform and gradient waveform are converted to analog signals and amplified by power amplifiers to drive coils. After MR signal comes forth, pulse controller startups the RF receiver to sample it. The system controller processes sampling MR signal through digital quadrature detection and filtering. Finally, the k-space data is acquired.

The platform and system controller we employed are PXI 2630 and PXI 3710, products of ADLINK Technology Inc. PXI 6608 of National Instruments Corporation is used as pulse controller, which provides 8 32-bit timers. In the following, the design ideas of RF transmitter, RF receiver and gradient generator are discussed in detail.

B. RF Transmitter

RF Transmitter produces RF pulse for MRI system to excite nucleus. The magnetic field strength varies linearly due to gradient magnetic fields. Correspondingly resonance frequency of nucleus varies linearly. So RF pulse should be a narrow band modulation signal with center frequency equal to resonance frequency. The resonance frequency is determined by main magnetic field strength and slice location, and band width is determined by slice thickness. Considering the main magnetic field strength is B_0, slice location is x_1, slice thickness is Δx and gradient magnetic field is G_x. We can calculate the center frequency with Larmor formula as $\omega_0 = \gamma\left(B_0 + x_1 \cdot G_x\right)$, and band width is $\Delta\omega = \gamma \cdot \Delta x \cdot G_x$.

DDS is now widely used for RF pulse synthesis. The hardware design is complex. We present a software method to generate digital RF pulse. The block scheme is shown in Fig. 2. The algorithm is presented below.

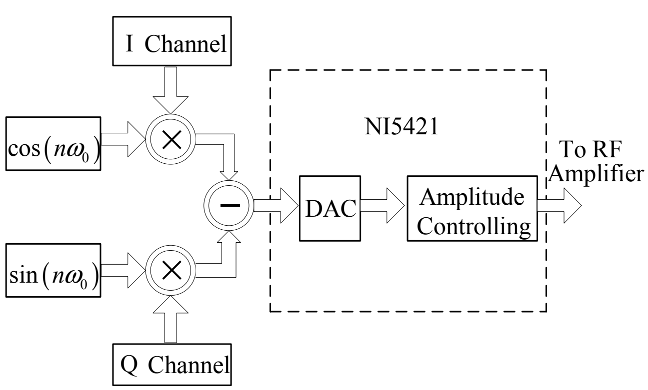

Fig. 2. Block diagram of RF transmitter

1) Calculate the center frequency of RF pulse, $\omega_0 = \gamma\left(B_0 + x_1 \cdot G_x\right)$, then the digital carrier can be generated as in (1).

$$S_c\left(n\right) = e^{i \cdot n\omega_0} = \cos\left(n\omega_0\right) + i \cdot \sin\left(n\omega_0\right) \qquad (1)$$

2) Define the amplitude $A\left(n\right)$ and phase $\theta\left(n\right)$ of baseband signal according to the scan sequence. The digital baseband signal can be represented by:

$$\begin{aligned} f\left(n\right) &= A\left(n\right) \cdot \cos\theta\left(n\right) + i \cdot A\left(n\right) \cdot \sin\theta\left(n\right) \\ &= I\left(n\right) + i \cdot Q\left(n\right) \end{aligned} . \qquad (2)$$

The real part and imaginary part are named as I channel and Q channel, respectively.

3) Modulate digital carrier with baseband signal:

$$\begin{aligned} S_t\left(n\right) &= \mathrm{Re}\left[f\left(n\right) \cdot S_c\left(n\right)\right] = \mathrm{Re}\left[A\left(n\right) \cdot e^{i \cdot \theta(n)} \cdot e^{i \cdot n\omega_0}\right] \\ &= A\left(n\right) \cdot \cos\left(n\omega_0 + \theta\left(n\right)\right) \\ &= I\left(n\right) \cdot \cos\left(n\omega_0\right) - Q\left(n\right) \cdot \sin\left(n\omega_0\right) \end{aligned} \qquad (3)$$

4) The digital RF waveform $S_t\left(n\right)$ is saved in the onboard RAM of DAC board. After the board is triggered by signal from pulse controller, digital waveform is converted to analog signal.

PXI 5421 of National Instruments Corporation is chose as DAC board. It is up to 256M onboard RAM to meet the needs of storage and provides function of amplitude controlling. RF signal is amplified by power amplifier to drive RF coil.

C. RF Receiver

MR signal caused by phenomena of magnetic resonance is amplified by the preamplifier and then processed by RF receiver. In order to down convert the frequency of signal to zero-frequency, MR signal is usually down mixed to intermediate frequency, and then analog quadrature detection is performed. Spectral distortion is often resulted in with this method due to amplitude and phase errors between two channels.

We directly sample the MR signal. Then the digital signal is processed by system controller. The block scheme is displayed in Fig. 3.

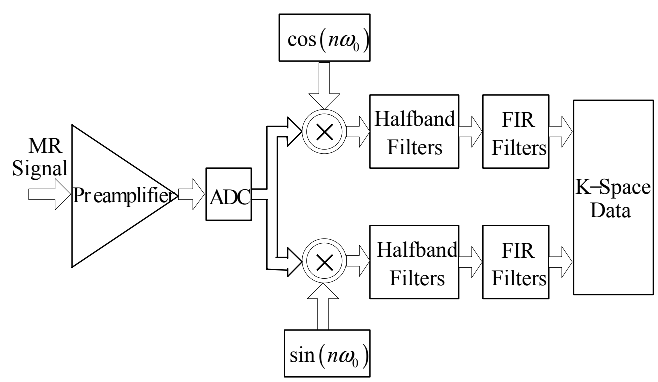

Fig. 3. Block diagram of RF receiver

The preamplifier firstly amplify MR signal to meet the input range of ADC board. The ADC board we used is PXI 9820 produced by ADLINK Technology Inc. After sampling, digital quadrature detection is executed. The aim of quadrature detection is to down convert the frequency to zero-frequency, and get the real part and imaginary part of MR signal, respectively.

Considering that digital MR signal received is $S_0(n)=\cos\left[n(\omega_0+\delta)+\phi\right]\cdot e^{-n/T_2}$, where δ is resonance frequency offset, ϕ is phase shift and T_2 is transverse relaxation time. The quadrature demodulation is multiplication of MR signal by sinusoid and cosinusoid with frequency at ω_0. We construct the sinusoid sequence $\sin n\omega_0$ and cosinusoid sequence $\cos n\omega_0$, and multiply by $S_0(n)$.

$$\begin{aligned} S_1(n) &= \cos n\omega_0 \cdot S_0(n) \\ &= \left[\cos(n\delta+\phi)-\cos(2n\omega_0+n\delta+\phi)\right]\cdot e^{-n/T_2} \end{aligned} \quad (4)$$

$$\begin{aligned} S_2(n) &= \sin n\omega_0 \cdot S_0(n) \\ &= \left[\sin(n\delta+\phi)+\sin(2n\omega_0+n\delta+\phi)\right]\cdot e^{-n/T_2} \end{aligned} \quad (5)$$

There are high frequency components in $S_1(n)$ and $S_2(n)$. The digital filter is needed to process signals. It is difficult to design a one stage filter because the difference between center frequency ω_0 and frequency offset δ is significant. We construct a two stage filter, which can be implemented easily.

The first stage is a group of half band filters. The response characteristics of these filters are undesirable, but they are efficient at handling high data bandwidths and reducing the data bandwidth by a factor of 2. The main feature of half band filter is half of coefficients are zeroes, which increases the speed of calculation. With the group of filters, the band width of signal has a reduction of $2^\wedge n$. The second stage is an FIR filter. Its coefficients are programmable and dictate the response characteristics of filter. After digital filtering, the real part and imaginary part are acquired. K-space data is written as

$$S(n)=S_1(n)+i\cdot S_2(n)=\left[\cos(n\delta+\phi)+i\cdot\sin(n\delta+\phi)\right]\cdot e^{-n/T_2} \quad (6)$$

which is used to analyze spectrum and imaging through Fourier transform.

D. Gradient Generator

Imaging objects are spatially encoded by gradient magnetic fields. Gradient generator provides gradient fields which can be switched rapidly. In our system, digital gradient waveform is calculated and converted to analog signal by DAC board. DAC board employed is PXI 6733 of National Instruments Corporation. The block scheme is displayed in Fig. 4.

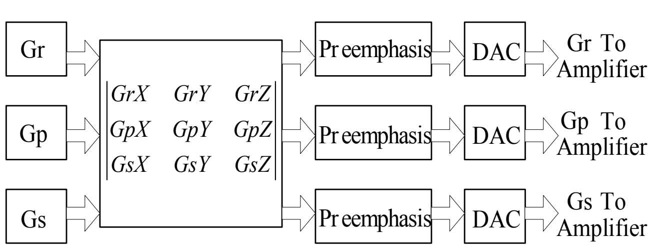

Fig. 4. Block diagram of gradient generator

There are three logic gradients defined in scan sequence, read-out gradient *Gr*, phase encoding gradient *Gp* and slice selective gradient *Gs*. They are not always identical with physical X, Y and Z-axis gradients in MRI system due to oblique angle imaging. In order to transform logic gradients to physical gradients, 3 odditional parameters are defined for every logic gradient respectively. For example, *GrX*, *GrY* and *GrZ* are defined for *Gr*. Hence a rotation matrix of space-oriented is constructed as

$$\hat{O}=\begin{vmatrix} GrX & GrY & GrZ \\ GpX & GpY & GpZ \\ GsX & GsY & GsZ \end{vmatrix}. \quad (7)$$

Physical gradients can be acquired through multiplying digital logic gradients calculated according to scan sequence by rotation matrix as (8).

$$\begin{vmatrix} Gx & Gy & Gz \end{vmatrix}' = \begin{vmatrix} Gr & Gp & Gs \end{vmatrix} \bullet \hat{O} \quad (8)$$

The rapid switches of gradient fields will cause eddy current. A pre-emphasis method is used to compensate gradient in our spectrometer. The method adjusts digital physical gradient waveforms before D/A conversion. Compensation function is $G(t)=\sum_{i=1}^{4} A_i\cdot e^{-t/T_i}$, which has 4 pairs of programmable time parameters and amplitude parameters. The final output gradients of X, Y and Z-axis are added by compensation values respectively. Digital gradient waveforms are converted to analog signal by DAC board and amplified by power amplifier to drive gradient coils.

III. Results

The spectrometer is connected to a 0.35 T MRI system, which uses open type permanent magnet. Larmor resonance frequency of proton is about 14.9 MHz. The RF amplifier is MODEL 231P of Copley Controls Corporation, and the gradient amplifier is AN8295 of Anologic Corporation.

Partial saturation sequence is performed to acquire free induction decay (FID) signal. The bandwidth of RF baseband signal is 20 KHz. The other experimental parameters are: RF pulse width D1 = 0.5ms, number of scans NS = 2, repetition time TR = 0.5s, dwell time DW = 0.02 μs, sampling time ST = 20ms.

FID signal of proton is acquired as shown in Fig. 5, which is a modulated signal. With Fourier transform, the spectrum of FID signal is shown in Fig. 6. We can see the center frequency is about 14.9MHz and bandwidth of signal is narrow. Then we demodulate the FID signal with the proposed method. Number of final data points is 256. The real part and imaginary part of demodulated FID signal are shown in Fig. 7. The spectrum of demodulated signal is shown in Fig. 8. We can see that FID signal has been down converted to zero-frequency and bandwidth is 485Hz.

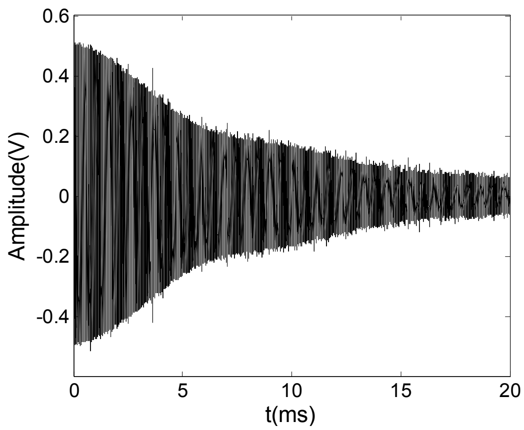

Fig. 5. FID signal of proton before demodulation

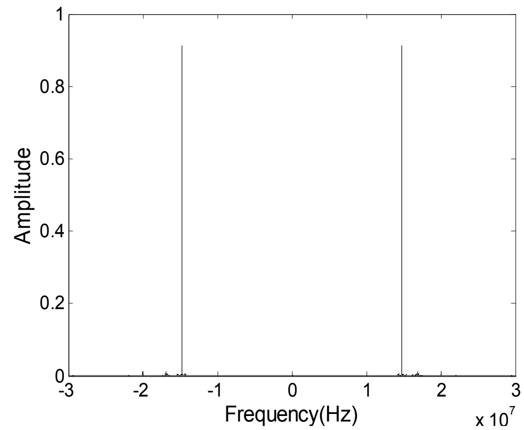

Fig. 6. Spectrum of FID signal before demodulation

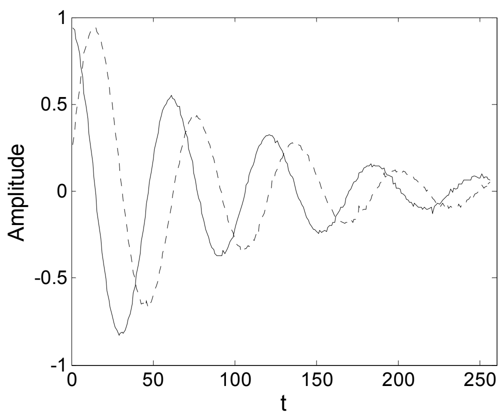

Fig. 7. Real part and imaginary part of demodulated FID signal. Solid line represents real part and dot line represents imaginary part

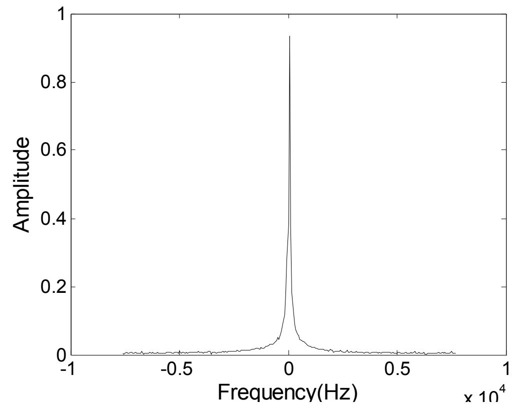

Fig. 8. Spectrum of demodulated FID signal

IV. Discussion and Conclusion

A novel MRI spectrometer based on PXI platform is presented in this paper. PXI platform provides many electrical signals served for synchronization and triggering. The frequency, phase and amplitude of RF pulse can be switched easily with digital synthesis. Application of digital quadrature detection avoids spectral distortion due to amplitude and phase errors between two channels. The experiment results demonstrate the efficiency and accuracy of the proposed spectrometer. By using this spectrometer design, MR signal can be acquired and processed correctly.

In the future, our research will be focusing on further improving the performance of spectrometer and implementing varies of scan sequences to imaging in terms of various applications.

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