A Complete Digital Magnetic Resonance Imaging (MRI) System at Low Magnetic Field (0.1 Tesla)

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Abstract- A new complete digital MRI system is developed to enhance the signal-to-noise ratio of the detected nuclear magnetic resonance (NMR) signals at low magnetic field (0.1 Tesla). The system is based on digital signal processor (DSP) that functions also as a controller and as an interface between the frequency translator and the digital synthesiser. The final system should be “portable” functioning at low voltage. It is a low cost system, and it can be dedicated to be used in a medical cabinets for examining small members of the human body. Such a system is also useful for quality control of agricultural and food products. The first results obtained with our system are presented in this paper. This includes NMR signal and images of 64x64 pixels.

Keywords- Low field MRI, NMR signal detection, Digital NMR system, NMR signal to noise ratio enhancement

I. INTRODUCTION

As it is well known, in MRI technique, a substance is subject to a uniform static magnetic field (polarizing field). A net magnetic moment, of the substance, is produced in the direction of the polarizing field. A short radio frequency pulse (RF excitation pulse) is applied at the characteristic Larmor frequency of the processing nuclei which, in turn, emit an RF signal (NMR signal) of the same frequency [1]. This signal is detected and processed to be used for obtaining a “fingerprint” of the environment of the nucleus being studied. This information is one-dimensional but is converted into two-dimensional image by adding gradients to the static magnetic field which results in a frequency modulation of the emitted NMR signal. A series of such measurements is analyzed by computer to generate the image [2], [3].

A typical MRI facility consists a magnet which produce the static field, an RF transmitter providing the RF excitation pulse and an RF receiver allowing detection and processing of the NMR signal. The MRI technique requires very expensive workstations because of the high static magnetic fields actually used. In our laboratories, we are working on the development of a dedicated low field (so low cost) MRI imager, at 0.1 tesla. This imager can also be used in medical cabinet for examining small parts of the human body (such as the arm, the wrist, etc.). The same system is useful for in-line quality control in agricultural and food applications[1] [8]. The major problem associated with the low magnetic field is that the NMR signal-to-noise ratio is very low and enhancement on signal processing are necessary. For doing so, we developed a whole digital MRI system.

Recently there are more and more digital parts in the MRI systems. However, the most important parts of the systems like frequency translators, filters, and synthesisers are still analog.

In the few last years, the high frequency digital systems was advancing very fast by proposing some new chips especially designed for new generations of digital mobile communications. The demands are so huge so that the enhancement to price ratio are so important especially when the design is needed for base stations. We show, in this paper, that these advances in digital technologies are of great value for improving MRI systems. So, a complete home-built MRI system is presented here. This system allowed us to obtain real signals to validate a nonlinear identification approaches of NMR systems. The interested reader may refer to references [5], [6], and [7] for more details regarding these approaches.

II. THE HOME-BUILT MRI SYSTEM

Fig. 1 shows our implementation. Apart of the (antenna’s RF amplifiers) and the duplexer, the whole system is digital, including the synthesiser and the frequency translator.

The direct digital synthesiser (DDS) produces an analog carrier signal which can be controlled in both frequency and phase. This signal is amplified by the RF amplifier and sent, into the sample under study, via an RF antenna.

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This same antenna is used to receive the NMR signal (we call it FID signal for Free induction Decay). This analog signal is passed to the RF digital receiver for quadratic demodulation.

In the next sections we will show the RF systems for transmitter and the receiver. Some first results of NMR signals and images are also shown.

**II.1. The digital radio frequency transmitter:**

The core of the digital transmitter is the direct digital synthesiser (DDS), where the frequency is defined by a parallel interface programmed directly by the DSP. Our synthesiser design does not consist of any phase locked-loops that may normally need some analog parts. In the market there are many synthesisers based on the phase locked loops. These synthesisers have problems especially for rapid changing in frequency and suffer from the phase noise. Many synthesisers are tested and finally the AD9852 from Analog Devices is chosen due to its possibility of high signal-to-noise ratio and the good SFDR in the final stage. The programmable gain of 12 bits in the output was very interesting to calibrate the RF signal digitally by the DSP.

The existence of the on chip comparator and an additional DAC was important to synchronise the phase with the digital receiving part. The internal clock was running at 200MHz although good signal to noise ratios was also obtained for 100MHz. Only 32 bits of the frequency tuning word was used due to the receiver internal synthesizer which is limited to 32 bits. A differential RF transformer and amplifier are used to buffer the signal output. The synthesised output (about 4MHz) is amplified again by an RF power amplifier designed in the laboratory.

Due to the 12-bit DAC output an excellent dynamic performance was obtained better than 75dB at 4MHz. The basic clock was derived directly from the DSP clock which is running at 40MHz.

In order to synchronize the phase of the RF output signal, the synthesized signal is compared to the additional internal DAC output that derives a firing start signal. This part was the most delicate part in the design due to the PCB optimisation and screening needed for a high signal-to-noise ratio.

Finally the possibility of programming the phase by the 14 bits of the synthesizer was very important to synchronize the receiver signal in real time, by programming a DSP loop frequency control system. The final RF power amplifier linearity was assured between 4 and 5MHz.

**II.2. Digital signal acquisition and processing:**

The NMR signal is detected by a well tuned RF antenna, the signal is matched to the RF preamplifier by a duplexer shown on Fig. 2. This amplifier is directly programmable by the DSP (10-30dB). The amplified signal is then sampled by a 12 bit analog-to-digital converter. The bandwidth of the RF amplifier and ADC was limited to 10MHz by using a $\pi$ section low pass filter (LPF).

In order to demodulate the NMR signal a complete digital tuner was used. This tuner can provide one channel digital receiver that translates the NMR signal to the base band using a 32 bit synthesizer and multiplier followed by decimation filters. The decimation factor as well as filter’s coefficients are completely programmable by the parallel bus of the DSP.

The receiver was designed as well as the transmitter part as a daughter board plugged on the main DSP Sharc PC board, interfaced with the PC via the PCI bus.

The DSP receives the demodulated base band signals (Real & imaginary parts) through its synchronous serial port clocked at 25Mbit/sec.
III. SYSTEM TESTS

In order to quantify our results concerning the signal to noise ratio, as well as noise rejection and sensitivity, the digital receiver was tested by applying a known signal level at the RF input.

The receiver’s digital synthesizer is tuned to 5 MHz, the sampling frequency was 50MHz, and the total decimation factor was 2000. This decimation factor yields base band samples each 40 µs. The decimation factor was calculated from two digital decimation filters. The first filter is a low pass filter which is used to compensate for the droop in the useful bandwidth and assures a flatness better than 0.01dB in the final bandwidth. The second decimation filter is designed to limit the bandwidth to 5kHz, as shown in Fig. 3. This bandwidth defines the usable NMR signal bandwidth during image acquisition which corresponds to about 6x10⁻³Tesla/meter of gradient field and 5.8kHz at –3dB. Also, the RF input amplifier is programmed to 30dB gain.

The test procedure was as follows : First, a pure sine wave of 5MHz is applied with a variable amplitude from –50dB to –130dB. The observed sensitivity for the digital receiver was –120dB. And the best dynamic range for the digital full scale output was at –96dB. Secondly, a swiped sine wave was applied to valid the cut-off frequency of the whole bandwidth, especially the final decimation filter’s frequency response as shown in Fig.3. Finally, the noise rejection was tested by introducing a wide band noise of 4MHz bandwidth on each side band (+/- 50KHz) with SNR=0dB. The results show a total rejection of the noise which was beyond our measuring instrument.

Fig. 2: The RF digital receiver.

Fig. 3: The impulse and frequency response of the decimation filter.
IV. REAL NMR SIGNALS AND IMAGES

The results are obtained in a 0.1 Tesla magnetic field created by an Electro-magnet\(^2\). It has some 10\(^{-3}\) of homogeneity in a volume of about 100 cm\(^3\). The antenna is made of 6 spires coil coupled with a capacitor tuned antenna. The same antenna was used for transmitting and receiving the NMR signals using an appropriate matching circuit. The sample under investigation was a cylindrical tube filled with pure water.

The sampling frequency of the NMR was fixed to 50 MHz. This frequency was optimum for the digital filters used in the receiving section. The decimation factor was 2000 so that the final signal output sampling rate is 25 kHz. Fig. 4 shows the FID signal (real and imaginary parts) obtained as a response to \(\pi/2\) flip angle pulse of 2 ms.

![Fig. 4: The real and the imaginary parts of the NMR FID signal.](image)

In order to define a precise NMR imaging sequence, a Windows98 based sequencer is developed. The sequencer generates a file from the defined graphical interface with which the user can easily define all possible sequence timing parameters including sequence type, image resolution, slice thickness, and the field of view. This generated file will be interpreted by the DSP-SHARC to generate the different signals (XYZ gradient, Control signals, RF excitation pulse envelope, etc.).

Images of 64x64 pixels are obtained using a gradient-echo imaging sequence. Sequences are programmed by DSP assembly language. The obtained resolution for the average of 8 successive images is shown in Fig.5. This resolution is about 1.6 mm/pixel

![Fig.5: 64x64 pixels images obtained with the gradient-echo imaging sequence (echo time TE=6ms, repetition time TR=1.2s, slice thickness is of 1cm). The cylindrical tube of filled with water (on the top) and the same tube with inserted plastic object in the center.](image)

V. CONCLUSION

We demonstrated, in this paper, that the implementation of a digital MRI system is possible by using advances in digital technologies. This system, which is low cost and friendly use, allowed us to obtain high NMR signal to noise ratio for both low field spectroscopy and high resolution imaging applications.

As a future work, ultra fast sequences will be developed for real time NMR imaging which is more and more necessary for many industrial applications.

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REFERENCES


\(^{2}\) Made by the company DRUCH (France).


