An acquisition system of digital nuclear signal processing for the algorithm development

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Abstract A principle and method of constructing the digital acquisition system is presented in this work, which is convenient for the study on the theories and algorithms of digital nuclear signal processing. The hardware system of the digital acquisition system consists of front-end controller, waveform digitizer and PC workstation, on which the software system has been developed based on Visual C++ under Windows environment. The alterable-frequency sampling (AFS) algorithm and the alterable-frequency trapezoidal filter (AFTF) algorithm have also been studied in the real-time environment, along with a digital nuclear spectrum acquisition system being set up based on the new algorithms and the γ-ray spectra of ^{241}Am being shown. A useful experimental platform could be provided by this work for the successive work such as the development of global digitized nuclear measurement system and the study of digital nuclear signal processing.

Key words Digitized nuclear instrument, Digital nuclear signal processing, Digitized nuclear measurement

1 Introduction

Digitized nuclear instruments are widely used in the domain of digitized nuclear measurement in recent decade[1-3]. Generally, digitized nuclear instruments are composed of concise and compact hardware, as well as software including various functions and algorithms, which have features as light weight, small size, low cost, easy operation and good performance when supported by good signal processing algorithms[4–6]. Thus the study on theories and algorithms of digital nuclear signal has become an important research direction within the domain of digital nuclear instrument. It is necessary to develop a digital acquisition system for the study and experiment of nuclear signal processing, which should have features as follows:

(1) The digital acquisition system should have good compatibility and expansibility of software, which is convenient for already existing algorithms to be added in and provides interface to new algorithms.

(2) The digital acquisition system should have ability of both on-line and off-line data processing, which can not only verify the efficiency and real-time of algorithms but also provide resources for the study of high-precision algorithms.

(3) The digital acquisition system should have functionality of good visualization, in which multi results can be shown simultaneously and saved automatically.

(4)The digital acquisition system should have functionality of easy and flexible adjustment of hardware parameters for various experiments.

Based on considerations above, a platform of the digital acquisition system has been constructed for the research and development of theories and algorithms used for digital nuclear signal processing, as is shown in Fig.1. The waveform digitized system is composed of the "PCI-9820" waveform digitizer provided by

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AD-LINK and the front-end controller designed by ourselves. The acquired digital nuclear signal is transferred to high-performance PC workstation via PCI bus for storage and further procession on-line or off-line. The software system has been developed based on Visual C++ under Windows environment. The software system includes two main parts, one is basic module which includes the essential software such as sampling control, data storage, real-time display sub-modules, and the other is expansive module which is designed for the study on new algorithms of digital signal processing. The new algorithms can be integrated into the software system in form of modules and called by kernel programs. The expansive module will be continuously expanded with the development of new algorithms, which makes the software system keep improvement with the deep research of digital signal processing. In order to validate feasibility of the digital acquisition system discussed in this paper, a digital nuclear spectrometer was set up, where the traditional trapezoidal filter (TTF) algorithm, AFS algorithm and AFTF algorithm have been embedded into. Finally, the measured γ-ray spectrum of ^{241}Am is demonstrated.

2 Construction of waveform digitization system

The nuclear waveform digitization system has been constructed with the core of "PCI-9820" digitizer provided by AD-LINK. The gain-adjustable front-end controller has been designed for the sake of matching the amplitude of signal output from semiconductor detectors with the input range of digitizer, which can decrease the quantization error effectively. The front-end controller is connected to nuclear detectors, by which the analog signal from detectors has been magnified to suitable amplitude to fit the digitizer for minimizing the quantization error and amplitude loss during waveform digitization[7].

2.1 Principle of the front-end controller

The gain-adjustable front-end controller is designed according to the principle for determining amplification above, which is completed by adjusting the amplification of amplifier through controlling digital potentiometer via CPLD. It consists of input select unit, differential shaping unit, gain adjustment unit, channel switching unit, controlling unit and power supply unit. Fig.1 shows the structure diagram of the front-end controller.

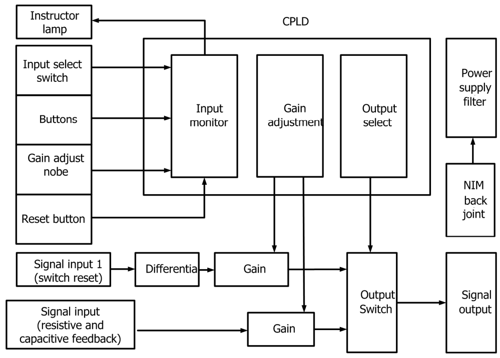

Fig.1 Structure diagram of the front-end controller.

The output mode of the preamplifier can be selected as resistive and capacitive feedback or switch reset, which is controlled by the input select unit. The AC coupling of the signal is completed by the differential shaping unit. The signal is magnified to fit the input range of the digitizer followed by the gain adjustment unit. The followed output channel selection is dominated by the channel switching unit which is realized by the chip MAX-4729. The core of the controlling unit is a CPLD（XC-95288XL）,which is programmed to implement system reset, indicator lamp control, channel switch control and digital potentiometer setting. According to the status of dial switch, corresponding timing sequence is sent out to set up the value of digital potentiometer by CPLD, thus the amplification of the gain adjustment unit can be regulated.

2.2 Constitution and performance of the waveform digitizer system

The main parameters of the digitized nuclear signal acquiring system are as follows: double channels and the bandwidth of small signal of each channel is above 30 MHz; the conversation range of ADC can be programmed to ±5 V or ±1 V; each channel has a separate 14-bit ADC; the maximum sample rate of each ADC is 65 MS/s and the maximum sample rate of the digitizer can reach 130 MS/s when used as "ping pang" mode; onboard 128M SDRAM is used as data buffers. The data is transferred from buffers to PC workstation via DMA mode, used for dynamically displaying, real-time progressing or data saving by the software.

3 Design of software

The software system of the digital acquisition system platform is developed under Visual C++, which contains the basic module and the expansive module. The basic module includes several sub-modules such as parameter setting, sample controlling, basic signal processing, graph displaying, through which we can complete the fundamental functions of the platform software such as waveform sampling, data saving, dynamical waveform plotting, energy spectrum displaying and so on. The expansive module is designed for users to add successive signal processing algorithms for specific applications. The algorithms are encapsulated as DLLs (dynamic link library), which can be easily integrated into the software system according to pre-defined user interface. So far, the algorithms of AFS and AFTF are accomplished in our software. Fig.2 shows the structure diagram of the platform software.

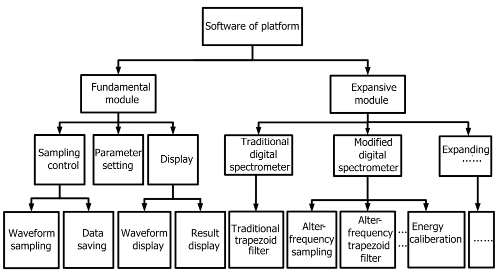

Fig.2 The structure diagram of the platform software

3.1 Design of parameter setting and sampling control modules

By calling the API functions of SDK provided by PCI-9820, we can not only complete the parameter setting of PCI-9820 digitizer such as sampling frequency, sampling mode, triggering mode, triggering level, calibration mode, input range etc., but also control the digitizer to start working or stop working[8]. The sampled real-time data acquired by the digitizer is first stored in onboard buffer, and then transferred to the computer memory via DMA mode through PCI bus when the buffer becomes full. The real-time data may be used for further handling with associated signal processing algorithms and the result may be dynamically displayed or saved as data files in our software.

3.2 Design of expansive module

The expansive module consists of various algorithms of nuclear signal processing which are in the form of DLLs and can be conveniently added to the software system followed by specific rules. In this work, firstly, the traditional digital trapezoidal filter algorithm has been integrated into the expansive module, along with the basic module, forming a traditional digital nuclear spectrometer, which is used for basic performance test of the platform and for comparing with other experiments. Next, the AFS algorithm and AFTF algorithm of digital nuclear signal based on digital decimation are developed, which is used to set up an improved digital nuclear spectrometer with the optimal data amount.

3.2.1 Extract of waveform data

The digitized data continuously sampled by the digitizer includes both the data of nuclear events and the data of intervals between nuclear events. When the rate of nuclear events is low, a lot of storage resource will be wasted if all of the continuous data are saved. The algorithm of AFS and AFTF mentioned in the next paragraph both handle the single waveform, so the data to be saved is only the whole waveform data extracted from the original continuous sampled data. Consequently we design a specific data structure to store the waveforms

```
Struct PulseWave
{   ULONG startTime; //the start time of waveform
    ULONG endTime; // the end time of waveform
    USHORT peakValue; //the peak value of waveform
    ULONG peakTime; // the peak time of waveform
    USHORT *pValue;//the data of waveform}
```

In this data structure, the data members “startTime” and “endTime” record the start time and end time of every waveform respectively. The data member “*pValue” is the pointer to an array of the sampled discretized data of every waveform from the start time. The "peakValue" and "peakTime" record the peak value and the peak timestamp of every waveform, which provides necessary information for successive signal processing algorithm to enhance computing efficiency. By the use of the data structure, we can largely decrease the amount of storage while saving the effective waveform information.

3.2.2 Algorithm of AFS

In order to preserve the entire information carried by the nuclear signal during digitalization, the massive data receiving and processing must be effectively executed. The output signal of preamplifier is usually double exponential signal with nanosecond-micro-second rising edge and microsecond-millisecond falling edge. The rising edge of nuclear signal lasts shorter time and consists of large high frequency contents that may contain nuclear events; whereas the falling edge consists of low frequency contents but takes many storage resources due to its long duration. In order to utilize the storage resource effectively[9], a noval, namely "alterable-frequency sampling (AFS)" sample method is performed by following steps: First of all, digitalizing the nuclear signal with high frequency sampling, then making the falling edge of the signal low-pass filtered and extracted with lower sampling frequency; and finally combining the rising edge of the high frequency sampled signal with the falling edge extracted with lower frequency sampling to form a new waveform and save it.

According to the Nyquist law, the original signal should be processed with anti-aliasing digital filter in order to eliminate the frequency aliasing during sample extracting. Assuming the output of the preamplifier is $x(nT)$, and $y_D(nT)$ is the output after M times of extracting, then $y_D(nT)=x(MnT)$.

The output of $y_D(nT)$ after low-pass anti-aliasing filter is $y_{DLP}(nT)$, then the output of AFS can be described as Eq.(1)

$$y(n)=\begin{cases} x(nT), & n \le N_p \\ y_{DLP}(nT), & n > N_p \end{cases} \tag{1}$$

where N_p is the time of peak.

3.2.3 Algorithm of AFTF

The trapezoidal shaping filter is one of the most common optimal filter for nuclear signals which is adequate for best energy resolution and high throughput general application[10–14]. Here we design a new algorithm of trapezoidal shaping used for double exponential signal after AFS. Unlike conventional trapezoidal shaping algorithm, the double exponential signal is divided into rising edge section and falling edge section split by the peak. The rising edge section is directly shaped by trapezoidal shaping algorithm, whereas the falling edge section is firstly handled by frequency reduction and then shaped by trapezoidal shaping algorithm. Finally the two sections of shaped signals are combined into one signal by a specific method. The pulse width and flat top width of the shaped signal can be adjusted flexibly through parameter setting.

Assuming the input signal is described as Eq.(2),

$$v(nT)=k\left(e^{-\frac{nT}{\tau_1}}-e^{-\frac{nT}{\tau_2}}\right) \tag{2}$$

where τ_1 and τ_2 are the time constant of rising edge and falling edge of the signal respectively.

The impulse response function of trapezoidal shaping filter is described as the following formula.

$$h(nT)=h_1(nT)+h_2(nT)+h_3(nT)+h_4(nT) \tag{3}$$

where

$$\begin{cases} h_1(nT)=k\left(\frac{\tau_1\tau_2}{\tau_1-\tau_2}\delta(nT)+\frac{\tau_1+\tau_2}{\tau_1-\tau_2}+\frac{n}{\tau_1-\tau_2}\right)u(nT) \\ h_2(nT)=\text{-}h_1(nT-t_1) \\ h_3(nT)=\text{-}h_1(nT-t_2) \\ h_4(nT)=\text{-}h_1(nT-t_3) \end{cases} \tag{4}$$

In formula (4), t_1 is the end time of the rising edge, t_2 is the start time of the falling edge, t_3 is the end time of the falling edge, k is the normalized slop of the straight.

The shaped result of rising edge section of the signal is described as the following formula.

$$y_r(nT)=h(nT)\times x_r(nT) \tag{5}$$

where $x_r(nT)=\begin{cases} v(nT), & n \le N_p \\ 0, & n > N_p \end{cases}$

$$y_f(nT)=h(MnT)\times x_f(nT) \tag{6}$$

where $$x_{\mathrm{f}}(nT)=\begin{cases} v(MnT), & n>N_{\mathrm{p}} \\ 0, & n\le N_{\mathrm{p}} \end{cases}$$

The result of AFTF is the combination of the two above shaping results calculated by formula (7)

$$y(nT)=y_{\mathrm{r}}(nT)\times M\cdot y_{\mathrm{f}}(nT) \qquad (7)$$

where M is the frequency reduction multiple.

4 Performance of the digital acquisition system and the test of algorithms

4.1 Basic function of the system

The digital acquisition system platform has the basic functions as follows:

(1)The sample rate can reach 130MHz for single channel and 65 MHz for double channels with the effective number of bits of 14.

(2)The sample parameters and amplitude gain of analog signals can be optimally adjusted.

(3)The functions of real-time acquisition and dynamic displaying of nuclear signals can be achieved.

(4)The user-defined algorithms can be integrated into the platform for on-line or off-line test.

(5)The results of signal processing algorithms can be visualized.

4.2 Test result of the performance of front-end controller

Fig.3 shows the experimental result of the γ-ray of ^{241}Am with front-end controller, in which the top waveform is direct output of CZT detector and the bottom waveform is the output of the front-end. As shown, the signal of output of CZT detector is magnified through the front-end controller, of which the time constant of rising edge and falling edge is coincided with the output of detector.

4.3 The test result of the basic module

Fig.4 shows main software interface of the digital acquisition system, which implements the functions of basic module such as parameter setting, control of waveform sampling, data saving, dynamical waveform or spectrum displaying and so on. The waveform is the real-time signals of the γ-ray of ^{241}Am detected by CZT detector and processed by the front-end controller, and finally sampled at the frequency of 60 MHz.

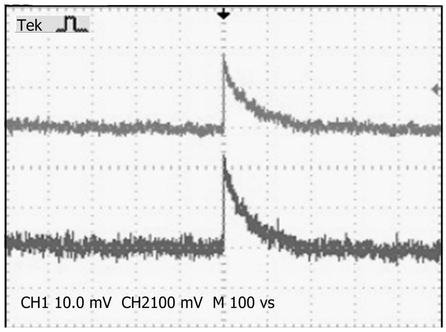

Fig.3 The experimental result of the output through front-end controller.

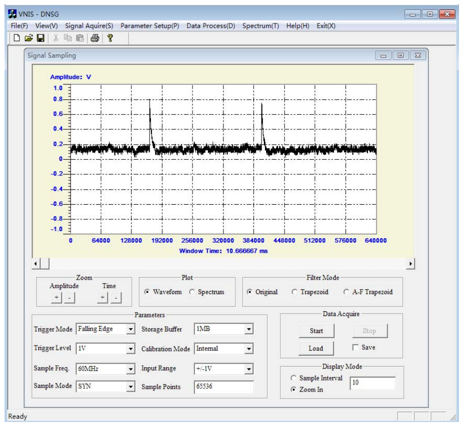

Fig.4 The main interface of software.

4.4 Determination of frequency reduction multiple

In order to evaluate the effect of the AFS algorithm, we introduce a parameter δ_s to describe the distortion extent of the sampled signal after frequency reduction, which is defined as formula (8),

$$\delta_s=\frac{t_a-t_b}{t_b} \qquad (8)$$

where t_a is the rising time or falling time of the signal after frequency extracting, t_b is the rising time or falling time of the signal before frequency extracting. The t_a or t_b is defined as the time interval from the value of 10% of the peak value to that of 90% for the rising edge and from the value of 90% of the peak value to that of 10% for the falling edge. Given a acceptable value of δ_s, e.g., δ_0 =3% in our case, we can increase the frequency reduction multiple step by step until we get the maximum frequency reduction multiple which satisfies $\delta_s<\delta_0$.

The sample frequency should be satisfied with the requirement of the time property of nuclear signals, which is determined by the output of the specific preamplifier. In our platform, the rising time of output pulse of our CZT detector system is about 0.5 us, which was measured by Lecroy WaveRunner digital oscilloscope with 10GSPS sample rate. The sampled pulse data has been saved as original data, from which we extract data with different frequency reduction multiples and calculate δ_s of those for the rising edge and falling edge of the pulse respectively. The result shows the sample frequency of 60MHz is optimal for the rising edge of the pulse and the sample frequency of 15 MHz is optimal for the falling edge of the pulse, with the distortion of 2.7% and 0.5% according to formula (8). So it is reasonable and feasible to study the above-mentioned algorithms with the sample frequency of 60 MHz under our detector system.

4.5 Test results of AFS and AFTF

Fig.5 and Fig.6 show the measurement results of γ-ray of ^{241}Am with CZT detector with our digital acquisition system of digitized nuclear instrument. The shaping parameters of trapezoidal filter are carefully selected[15]. The waveform 1 in Fig.5 is the original signal acquired by PCI-9820 digitizer, and the waveform 2 is the output signal processed by AFS algorithm and AFTF algorithm. Fig.6 shows the filtering results of the TTF compared with that of the AFTF algorithm, where the waveform 1 is filtering result of the conventional trapezoidal filter, and the waveform 2 is filtering result of the AFTF algorithm, where the frequency reduction multiple of the rising edge is 1 and that of the falling edge is 4 . From these two figures we can see the filtering results of the two algorithms are almost consistent.

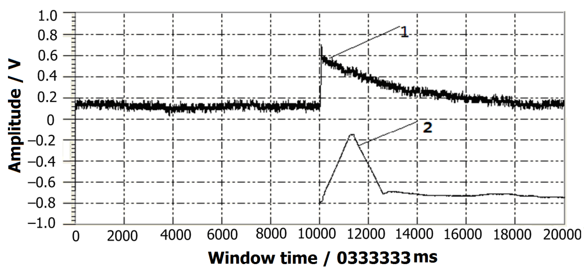

Fig.5 Measurement result of AFTF algorithm.

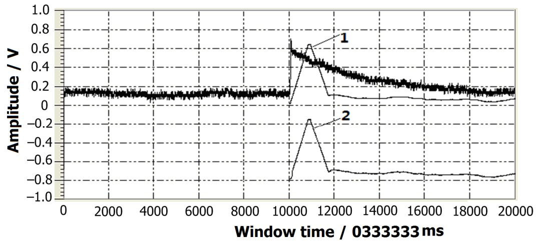

Fig.6 The comparison of traditional trapezoidal filter and AFTF.

4.6 Spectra measurement

4.6.1 Experimental apparatus

In order to verify the validity and feasibility of our scheme, we set up two experimental apparatus and test the output of CZT detector simultaneously, one of which is an conventional analog spectrometer composed of amplifier, MCA and software of data processing manufactured by ORTEC, the another is our digitized nuclear instrument platform consisting of front-end controller, digitizer and software of the digital acquisition system. Fig.7 shows the block diagram of the two experimental apparatus.

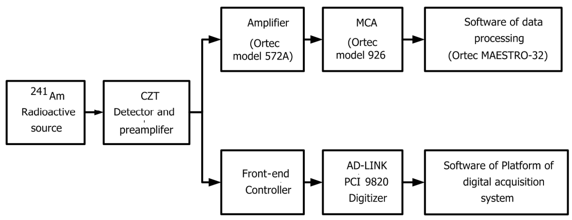

Fig.7 The block diagram of the experimental apparatus.

4.6.2 Measurement results and discussions

Figure 8(a) shows the γ-ray energy spectrum of ^{241}Am with CZT detector acquiring by the analog system in the upper half of Fig.7. Fig.8(b) and Fig.8(c) show the spectra acquiring by the digital acquisition system in the lower half of Fig.7, where the former using the TTF algorithm and the latter using the AFTF algorithm. In order to compare the energy spectra got by the two experimental apparatus accurately, the analog spectrum and the digital spectrum have been acquired simultaneously. The resolutions of peak at 59.5 KeV of the three spectra are respectively 9.7%, 6.6% and 6.8%. It can be seen from the figures that the energy resolutions of the spectra acquired by our digital acquisition system platform are better than that acquired by conventional analog spectrometer, especially from the two low energy peaks, which implies that the noise of output signals of CZT detector has been better rejected by digital filter of the digital acquisition system than analog filter of conventional analog system. Meanwhile, the resolutions of spectra in Fig.8(b) and Fig.8(c) are almost same, which means the AFTF algorithm does not affect the resolution of the spectrum apparently. The event rate of the analog system consists of ORTEC components is about 200 cps when we take energy spectrum acquisition under our experimental circumstance, whereas that of our digital system is almost the same for both the TTF algorithm and the AFTF algorithm.

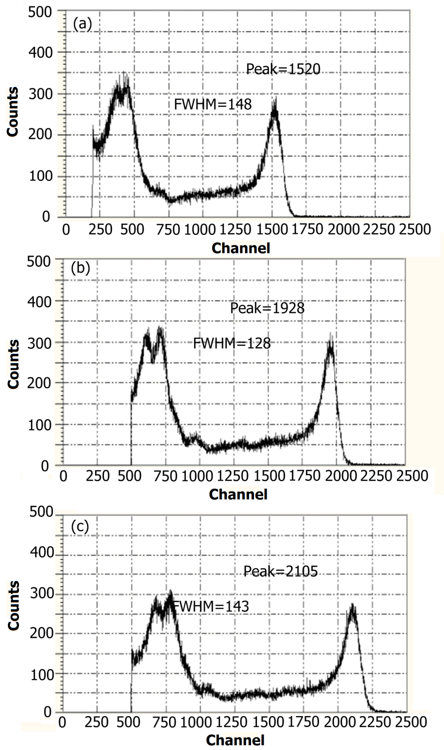

Fig.8 γ-ray energy spectra of ^{241}Am with CZT detector under different conditions. (a) The spectrum acquired by conventional analog system. (b) The spectrum acquired by digital acquisition system with TTF algorithm. (c) The spectrum acquired by digital acquisition system with AFTF algorithm.

5 Conclusion

According to the result of experiments, a summary of our study is given as follows:

(1) The principle and realization method of the digital acquisition system discussed in this paper have been proved correct and feasible.

(2) The AFS algorithm and AFTF algorithm have been successfully developed and tested under our digital acquisition system platform.

(3) The traditional digital nuclear spectrometer and the optimal digital nuclear spectrometer provided with new algorithms have been implemented, and their performances have been compared experimentally.

(4) The digital acquisition system platform of digitized nuclear instrument may be a useful experimental platform for successive study of algorithms for digital nuclear signal processing.

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