Development of a Nuclear Energy Spectrum Signal Generator

Juan Zhai¹, Jiehao Chen¹*, Hongjian Lin¹, Jinge Zhou¹, Jinchu Huang¹

¹College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Chengdu 610059, Sichuan, China
Email: 1280142699@qq.com

Abstract. A digital nuclear pulse and digital nuclear energy spectrum signal generator was designed using FPGA and digital frequency synthesizer (DDS). It also includes slip signal, triangle wave, square wave, sine wave output. By randomly sampling the amplitude information and time information of the reference spectrum line, the complex algorithm of nuclear signal reproduction is avoided, and the simulation of the nuclear signal random pulse and nuclear energy spectrum ($^{137}$Cs gamma spectrum) is realized. The signal amplitude is adjustable from 0.1V to 10V, and the frequency is adjustable from 10Hz to 10kHz.

Keywords: FPGA; nuclear pulse; nuclear energy spectrum; DDS

1. Introduction
The acquisition of nuclear signals is usually obtained by using nuclear instruments to measure radioactive sources, and the waveform parameters of nuclear signals cannot be flexibly adjusted. The appearance of simulated nuclear energy spectrum signal effectively solves this problem. In addition, the nuclear signal source and the ordinary function signal source are mostly separated, and the integrated signal source of the two is rarely reported. With the development of digital circuits, a pseudo-random number algorithm can be used to obtain nuclear signal pulses [1], and a nuclear pulse model can be established by MATLAB, which can simulate nuclear pulse output. In this paper, multi-channel energy spectrometer is used to obtain specific standard nuclear energy spectrum data, and then random sampling is performed. At the same time, MATLAB and DDS principles are used to generate nuclear pulse analog signal, nuclear energy spectrum signal, triangle wave and other function signals. The simulation of nuclear energy spectrum signals and the integration of nuclear signal and function signal is realized.

2. Integrated Circuit Design
The signal generator is composed of clock circuit, FPGA module, DAC circuit, low-pass filter circuit, amplitude amplification circuit, human-computer interactive interface (waveform selection, LED display, frequency and amplitude adjustment) and power supply. As shown in figure1.
The working process: the mode control selects whether the output is nuclear signal or function signal. The waveform selection chooses the target output waveform. Then, setting the required frequency and amplitude. On the basis of the reference clock frequency, the FPGA reads the waveform data stored in the public storage ROM at a certain rate, and sends the data to the DAC to convert it into an analog signal, which is output after being amplified, filtered, and smoothed. The frequency and amplitude of the output signal are displayed by LED.
3. Implementation of System Algorithm

This paper simulates the characteristics of the nuclear signal in the FPGA through a specific algorithm—the randomness generated, the time interval follows the exponential distribution, the count rate follows the Poisson distribution, and the amplitude follows the Gaussian distribution, which realizes the output of the nuclear signal and function signal. Based on the DDS technology, the output of each signal waveform is realized.

3.1. DDS Principle and Function Waveform Realization

The DDS signal generator is shown in Figure 2. It is mainly composed of phase accumulator, phase modulator, waveform memory, DAC converter, and low-pass filter.

Suppose the \( Fcnt \) is a 32-bit register, the frequency control word is \( K \); the waveform data storage address depth \( A \) is 11 bits (A [10:0]), and the phase word is \( N \). The \( K \) passes through the accumulator \( (Fcnt<=Fcnt+K) \). After accumulating, the \( Fcnt \) value is registered in the phase register. Because the waveform data address depth is 11 bits, the higher 11 bits of \( Fcnt \) \( (Fcnt[31:21]) \), correspond to the waveform data address depth, and the lower 21 bits \( (Fcnt[20:0]) \), correspond to the accumulation of the \( K \). The ROM has stored the data of one complete cycle of the desired waveform. \( Fcnt[31:21] \) and \( N \) pass through the adder: \( Address<=Fcnt[31:21]+N \). Find the corresponding data by the value of \( Address \) in the ROM and transfer the data to the DAC to convert it into an analog signal, and then output it after low-pass filtering [2, 3].

The realization of sine wave, triangle wave and square wave is based on DDS technology. First, MATLAB generates 10-bit depth, 8-bit width waveform data and stores it in .mif format. The 10-bit depth (1024 sampling points) guarantees a good resolution of the output waveform without occupying more storage resources. Then the .mif format file is embedded into the FPGA internal ROM, and read out by the DDS technology.
3.2. Realization of Nuclear Pulse and Slip Signal

Nuclear pulse signals generated by nuclear radiation detectors usually take the form of exponential decay [4]. Use equation (1) to simulate the single pulse signal output by the nuclear detector in MATLAB.

\[ y = Ae^{(-t/\tau)} \]  

(1)

Where A is the output amplitude of the analog signal; \( \tau \) is the attenuation constant of the exponential signal; \( t \) is the time. Generate nuclear signal simulation model data in .mif format with 1024 sampling points. With the help of the DDS core in the FPGA, the final output nuclear pulse form exhibits an exponential decay shape.

The realization of the slip pulse signal is to control the FPGA by programming to generate the step amplitude signal and the holding time of the signal [5], the FPGA controls the amplitude value, count rate and pulse time of the DAC output. The pulse time and the number of channels determine the slip time. By controlling the pulse time, the slip period is controlled.

3.3. Realization of Nuclear Energy Spectrum Signal

Use the 3-inch NaI (Tl) detector and the digital multi-channel spectrometer to obtain the gamma spectrum measured from the \(^{137}\)Cs source as a sample reference spectral line, and store it in the ROM of the FPGA. Setting up the time and amplitude scanning module and random number module in the FPGA. Each module outputs \(^{137}\)Cs source nuclear signal according to the data of the reference spectrum. The study found that the simulation of nuclear energy spectrum signal needs to solve two problems: (i) the realization of the random amplitude generation of the signal, (ii) the realization of the random time generation of the signal. Using 32-bit pseudo-random number generator to randomly sample the signal amplitude and generation time can effectively solve problems [6].

Suppose that the number of nuclear energy spectrum channels collected by the multi-channel pulse amplitude analyzer is 512, the maximum energy is 662KeV, and the signal conversion gain is 1V/KeV. Each channel corresponds to a count value. The pulse counts of the \( n \)-th channel is \( N \), the cumulative pulse number of the first \( n \) channels is \( \text{total}[n] \), and the total pulse count value of the entire energy spectrum is \( S \). At the same time, the energy spectrum is divided into 512 intervals to achieve different probability distributions. The generated random number is \( X \). \( X \) takes the residual \( C \) for \( S \), and uses the successive approximation method to determine whether the value of \( C \) is in the interval \((\text{total}[n-1], \text{total}[n])\). If the \( C \) value is in the interval, a pulse with amplitude value of \( n \times 662/512 \) KeV is output, and the probability that the \( C \) value is in the interval \((\text{total}[n-1], \text{total}[n])\) is \( N/S \), so probability of the output of the pulse amplitude corresponding to the \( n \)-th channel is also \( N/S \). The output of the random pulse amplitude is realized by generating a random number.

The realization of generating signals at random time is the same as the realization principle of random pulse amplitude. The count rate of nuclear signal satisfies the Poisson distribution [7], and the average counting rate of the nuclear pulse corresponding to a certain channel is \( m \). Research by relevant scholars has shown that the time interval for nuclear signal generation follows an exponential distribution. Within the time interval \((t1, t2)\), the probability \( P \) of the occurrence of nuclear pulses is:

\[ P(t1 < t < t2) = e^{-mt1} - e^{-mt2} \]  

(2)

The average time \( \bar{t} \) in the time interval \((t1, t2)\) satisfies equation 3.

\[ \bar{t}(t1 < t < t2) = \left(ln\frac{e^{-mt2}-e^{-mt1}}{m(t2-t1)}\right)/m \]  

(3)

The time period of the next pulse appearing after the first nuclear pulse appeared is divided into 512 intervals. According to the reference spectral line data, equation (2) and equation (3) [6], the probability of pulses in different intervals and the average time of different intervals are calculated and saved in FPGA. The probability of nuclear pulses corresponding to the \( n \)-th interval is \( P_n \). The sum of the first \( n \) channel probability of occurrence of nuclear pulses in each interval is \( P_{\text{total}[n]} \), and the sum
of the probability of occurrence of nuclear pulses in all intervals is $P_{total}$. The random number generated by the pseudo-random number generator is $P_x$. $P_x$ takes the residual $P_c$ of $P_{total}$, and uses the successive approximation method to determine whether the $P_c$ is in the interval ($P_{total}[n-1], P_{total}[n]$). If the $P_c$ value is in the interval, the output time of the next pulse is the average time corresponding to the $n$-th channel, thereby realizing the randomness of the pulse generation time.

4. Test Results and Analysis

4.1. Output Test of Each Signal Model

![Figure 3. Nuclear signal output shape.](image)

It can be seen from the figure 3 that the function signal model output is normal, the nuclear pulse signal decays exponentially, and the nuclear energy spectrum signal exhibits amplitude randomness and time randomness. Parameter index as follow:

Function signal: (i) amplitude: 0.1V~10V, minimum adjustment step is 0.1V, relative error is 0.8%; (ii) frequency: 10Hz~1MHz, adjustment accuracy is 0.01kHz, deviation <0.005%.

Nuclear pulse signal: (i) amplitude: 0.1V~10V, minimum adjustment step is 0.1V, relative error is 1%; (ii) frequency: 0.01Hz~10kHz, adjustment accuracy is 0.01kHz, deviation < 0.005%. (iii) Pulse width: 1~12μs, the number is adjustable, the deviation <0.01μs.

Slip signal: (i) amplitude: 0.1V~10V, minimum adjustment step is 0.1V, relative error is 0.5%; (ii) frequency: 0.01Hz~10kHz, adjustment accuracy is 0.01kHz, deviation<0.008%. (iii) Pulse width: 0.3μs~12μs, the deviation<0.01μs. (iv) Slipping period: 2s~20s, the deviation <0.03%.

4.2. Amplitude Distribution of $^{137}$Cs $\gamma$ Energy Spectrum
The simulated nuclear energy spectrum signal is sent to a multi-channel pulse amplitude analyzer for testing. The results are shown in figure 4. Spectral lines 1 and 2 are obtained by measuring 480s and 120s respectively. The counts of each channel show a statistical fluctuation change compared with the original standard spectrum, which is consistent with the statistical fluctuation rule. The total count of the original spectrum is 1796340, and the total count of the spectral lines 1 and 2 is 2583010 and 897100 respectively. The two measurement lines are consistent with the shape and peak position of the original spectrum. The two measured spectral lines and the standard spectral lines were subjected to linear fitting analysis, and the lowest linearity after fitting was both 0.999. Therefore, the nuclear spectrum signal output by this signal generator can simulate the output of the NaI(Tl) probe.
5. Conclusion
The nuclear pulse signal generated by the signal generator is consistent with the random characteristic of the actual nuclear pulse in count rate and amplitude. The output frequency is adjustable. The signal generator can imitate the nuclear signal generated by radioactive sources with different activities, and realizes the integration of nuclear signal source and function signal source. It also has the characteristics of light weight, small size, and has the application prospect and social and economic benefits.

Acknowledgments
The authors thank to The College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Contract 2017YFC0602105 for the financial support of this study.

Reference
[1] Li D C, Yang L, Yuan S L 2007 Research on random signal generator based on nuclear pulse Electronics and Probing Technology 27(2): 223-226
[2] Ma S, Tang B, Wang R B 2015 Simulation of nuclear pulse signal based on MATLAB Electronic Quality (5): 60-62
[3] Ponikvar D 2018 An FPGA-based nuclear pulse generator with a prescribed amplitude distribution Nuclear Instruments & Methods in Physics Research 877: 371-374
[4] Fu D R, Ma S B, Nie G N 2017 Design and implementation of a pseudo-nuclear pulse random signal generator Nuclear Electronics and Detection Technology 37(1): 37-42
[5] Wang H H, Qi X G, Mu K L 2007 Development of all digital slip pulse generator based on FPGA+MCU Nuclear Techniques 30(7): 868-871
[6] Tan C J, Zeng G Q, Xiong C Y 2014 Research on nuclear pulse signal generator based on random sampling Atomic Energy Science and Technology (S1): 655-661
[7] Luo X L, Zhang L Q, Zhang J 2017 Design of a novel random nuclear pulse signal generator Nuclear Electronics and Detection Technology 37(9): 913-917