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Date: 2023-06-18T00:00:00+00:00

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Full Text

Preamble

Optimal Choice of Trapezoidal Shaping Parameters in Digital Nuclear Spectrometer Systems

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Abstract

The trapezoidal shaping method is widely applied to pulse amplitude extraction in digital nuclear spectrometer systems. Optimal selection of shaping parameters can improve both energy resolution and pulse counting rate. From the perspective of noise characteristics, ballistic deficit compensation, and pulse pile-up

characteristics, this paper investigates the optimal selection of trapezoidal shaping parameters. Through theoretical analysis and experimental verification, the optimal choice of parameters is found to be similar to triangular shaping: a longer rise time and shorter flat-top width.

Keywords

Trapezoidal shaping parameter, Energy resolution, Ballistic deficit, Pulse counting rate, Digital nuclear spectrometer

Introduction

Digital processing of nuclear signals has a history of over 40 years. As early as 1973, Koeman et al. used digital filters to process nuclear signals at the Philips laboratory^{1,2}. At that time, a digital filter was designed to transform nuclear signals into trapezoidal pulses, and an X-ray energy spectrum measurement system was established based on this digital filter³. However, due to hardware limitations—particularly the key ADC device being only 5 bits at 2.5 MHz—the digital measurement system failed to surpass analog systems in performance^{4,5}.

The trapezoidal filter algorithm offers advantages in ballistic deficit compensation, energy resolution, and pulse throughput, making it a common choice for digital nuclear signal processing worldwide. Companies such as Canberra, XIA, and ORTEC have incorporated trapezoidal shaping filters into their digital nuclear spectrometer product series⁶. While the trapezoidal shaping algorithm has been discussed by domestic universities and research institutes in China, these discussions have mainly focused on improvements to the trapezoidal shaper itself^{7–11}, with little research on the optimal selection of trapezoidal filter shaping parameters.

This paper examines the optimization of trapezoidal shaping parameters from the perspective of ballistic deficit compensation, noise filtering, and pulse pile-up characteristics. By comparing energy resolution and pulse counting rates across different trapezoidal filter shaping parameters, we aim to improve and strengthen the trapezoidal shaping algorithm for broader application in digital nuclear signal processing systems.

2 Trapezoidal Shaping Algorithm

The input exponential signal is shaped into an isosceles trapezoid with adjustable rise time and flat-top width. The trapezoidal expression in the time domain is described by Eq.(1)¹²:

$$Vo(t) = \sum_{i=1}^4 y_i(t)$$

where parameter Vo is the trapezoidal shaping output and $y_i(t)$ represents the four sides of the trapezoid, as shown in Fig. 1.

From Fig. 1, A is the signal amplitude, t_a and D are respectively the rise time and flat-top width of the trapezoid, $t_b = t_a + D$, $t_c = t_a + t_b$, and t_c is the total width of the trapezoid. The $\mu(t)$ is the step function. Let T_s be the sampling frequency, with $n_a = t_a/T_s$, $n_b = t_b/T_s$, and $n_c = t_c/T_s$. Equation (1) can be converted into Eq.(2) through Z-transform.

The expression of a single exponential function is $V_i(t) = Ae^{-t/\tau}$, where parameter A is the signal amplitude and τ is the time constant. After Z-transform, this is described as $V_i(z) = Az/(z - a)$, where $a = \exp(-T_s/\tau)$. The transfer function of a single exponential signal in the trapezoidal shaping process is shown as Eq.(3)¹³:

$$H(z) = \frac{Vo(z)}{Vi(z)} = \frac{(1-a)}{z^{n_c}} \cdot \frac{(1-z^{n_a})(1-z^{n_b})}{(1-z^{-1})^2}$$

3 Optimal Choice of Trapezoidal Shaping Parameters

Optimal selection of trapezoidal shaping parameters requires weighing the characteristics of noise filtering, ballistic deficit, pulse pile-up, and amplitude extraction to guarantee maximal throughput and the best energy resolution in digital nuclear spectrometer systems.

3.1 Noise Characteristics of Trapezoidal Shaper

While the trapezoidal shaping algorithm is typically analyzed in the time domain, it is equivalent to a filtering operation in the frequency domain. Since the result of signal filtering is important for subsequent pulse amplitude analysis, it is necessary to further explore the frequency characteristics of the algorithm.

Applying Fourier transform to Eq.(1) and the input signal $V_i(t) = Ae^{-t/\tau}$ yields Eq.(4):

$$Vo(j\omega) = \frac{A\tau}{1+j\omega\tau} \cdot \frac{\sin(\omega t_a/2)}{\omega/2} \cdot \frac{\sin(\omega(t_a+D)/2)}{\omega/2} \cdot e^{-j\omega(t_a+D)/2}$$

The modulus of Eq.(4) is described as Eq.(5)¹³:

$$|Vo(j\omega)| = \frac{A\tau}{\sqrt{1+(\omega\tau)^2}} \cdot \left| \frac{\sin(\omega t_a/2)}{\omega/2} \right| \cdot \left| \frac{\sin(\omega(t_a+D)/2)}{\omega/2} \right|$$

where the parameters are the same as in Eq.(1).

Equation (5) includes two factors: the former is an attenuation factor that decreases approximately inversely with increasing frequency, and the latter is an oscillating factor whose frequency depends on the trapezoidal parameters (rise time t_a). With $T_s = 25$ ns, $t_a = 1$ s, $t_b = 2$ s, and $\tau = 50$ s, the

amplitude-frequency response curve of the trapezoidal shaping filter is shown in Fig. 2.

From Fig. 2, when t_a is larger, the oscillation period is shorter and low-frequency components increase relatively, providing better inhibition of high-frequency noise. Considering only noise characteristics, a greater rise time yields better precision from the trapezoidal shaper and is more conducive to subsequent extraction of pulse amplitude information.

3.2 Ballistic Deficit Characteristics of Trapezoidal Shaper

In practice, the charge collection time (t_d) of a detector is greater than zero and varies with different pulses, generating ballistic deficit in amplitude extraction with analog filters and resulting in degraded energy resolution. It is therefore necessary to study the dependence between the shaping process and shaping time parameters.

If the detector current is constant and the total charge is Q during time T_D , with feedback capacitor C_f in the charge-sensitive preamplifier, the convolution of the input current signal and the preamplifier's pulse response function yields the preamplifier voltage waveform described by Eq.(6)⁸:

$$V(t) = \frac{Q}{C_f} \cdot \frac{t}{T_D} \cdot \mu(t)$$

The signal is sampled and processed with differential treatment as described in Eq.(7), where parameter $n_d = t_d/T_s$. The trapezoid is acquired by overlapping n_d spacing of 1 with amplitude $V'(n)$. When $n_b - n_a \geq n_d$, the parameters n_b and n_a are as in Eq.(2), ensuring at least one of the n_d trapezoidal flat sections is overlapped. The amplitude is then described by Eq.(8):

$$A = \frac{Q}{C_f} \cdot \frac{n_d}{n_b - n_a}$$

In the above discussion, as long as the trapezoidal flat-top width (D) is not less than the maximum charge collection time, the pulse amplitude is proportional to the ideal output amplitude (Q/C_f) and independent of T_D , meaning there is no ballistic deficit. Considering only ballistic deficit characteristics, the trapezoidal flat-top width should be larger to eliminate effects on pulse amplitude extraction and improve the system's energy resolution.

3.3 Pulse Pile-up Characteristics of Trapezoidal Shaper

Pulse pile-up directly affects not only effective extraction of pulse amplitude but also energy resolution and pulse counting rate. The choice of trapezoidal shaping parameters directly influences pulse pile-up behavior, as shown in Fig. 3.

From Fig. 3, Fig. 3(a) shows the original nuclear signal with a pulse interval time of 8 s. Fig. 3(b) shows that with a rise time and flat-top width of 5 s, there is no pulse pile-up and pulse amplitude information can be accurately extracted. Fig. 3(c) shows that with a 7- s rise time and flat-top width, there is partial pulse pile-up but amplitude information can still be accurately extracted. Fig. 3(d) shows that with a 10- s rise time and flat-top width, complete pulse pile-up occurs and accurate amplitude extraction becomes impossible. Considering only pulse pile-up characteristics, performance is better when the shaping parameters are smaller. As discussed above, as long as the interval is not less than the sum of the trapezoidal rise time and flat-top width, the shaped pulse does not affect amplitude extraction.

3.4 Summary of Parameter Selection

Based on the above discussion, the choice of trapezoidal shaping parameters must consider ballistic deficit, noise, pulse pile-up characteristics, and amplitude extraction in digital nuclear spectrometer systems. A longer rise time provides better noise filtering performance and higher energy resolution, while shorter shaping time reduces the probability of pulse pile-up and improves pulse counting rate performance. Therefore, the optimum filtering parameters are similar to triangular shaping: longer trapezoidal rise time and shorter flat-top width.

4 Experiment Analysis

A Moxtek Si-PIN detector (XPIN-XT type) and a 50 kV X-ray tube (MAGNUM series) were used to measure a steel ruler. The X-ray tube voltage was 20 kV and current was 2 mA. The rise time and fall time of the nuclear pulse signal before ADC were 50 ns and 3.3 s respectively, as shown in Fig. 4. The pulse sampling point sequence from the ADC (AD9224, 12-bit, 40 MHz) was shaped into a trapezoid in FPGA. The trapezoid was converted by DAC and sampled by oscilloscope, appearing similar to a triangle with shaping parameters of $t_a = 12$ s and $D = 0.5$ s (Fig. 5).

The energy spectrum was obtained from the same collection data processed with different trapezoidal shaping parameters, with piled-up pulses directly dropped out. The energy spectra are shown in Fig. 6; for clarity, only a portion of channel numbers is displayed. The energy resolution and pulse counting rates are shown in Table 1.

Table 1 Performance comparison of different shaping parameters

Shaping Parameter (Rise Time + Flat-top Width) / s	Energy Resolution / eV	Pulse Counting Rate
10 + 0.5	210	8998
12 + 0.5	195	8432
16 + 0.5	180	7623

Shaping Parameter (Rise Time + Flat-top Width) / s	Energy Resolution / eV	Pulse Counting Rate
20 + 0.5	172	7056
26 + 0.5	168	6494

From Table 1, as the rise time and flat-top width increase from 10 s to 26 s, the system's energy resolution improves from 210 eV to 168 eV, but the pulse counting rate decreases from 8998 to 6494. When the trapezoidal shaping time is longer, the energy resolution is higher but the pulse counting rate is lower.

5 Conclusion

The trapezoidal shaping method has been widely applied to pulse amplitude extraction and analysis in digital nuclear spectrometer systems. The choice of shaping parameters must give full consideration to noise characteristics, ballistic deficit compensation, and pulse pile-up. Reasonable selection of trapezoidal shaping parameters can improve both energy resolution and pulse counting rate. Experimental results show that trapezoidal shaping parameters should be chosen with the longest possible rise time to enhance filtering performance for better energy resolution in digital nuclear spectrometer systems. The flat-top width should be decreased to reduce the probability of pulse pile-up. Therefore, the best shaping scheme and optimal shaping parameters are similar to triangular shaping. The method in Ref.[13] provides an effective approach to correct the counting rate for longer shaping times.

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Note: Figure translations are in progress. See original paper for figures.

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