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Implementing method of optimum front-end conditioner based on Butterworth filter

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Abstract The front-end conditioner is an essential part of digital systems of nuclear spectrometer, which functions in two ways: (1) prevents saturation of the subsequent ADC; (2) limits the bandwidth of frequency to realize anti-aliasing. To realize the above-mentioned functions, an optimum front-end conditioner for a resistive feedback charge-sensitive preamplifier is designed. In the conditioner, the pole-zero compensation (P/Z compensation) technique was used to effectively filter signals from the preamplifier. The Butterworth filter was improved after the pole-zero position was optimally set up to shape the wave of output, which tallied with the whole system. The front-end conditioner can resolve the aberration of waveform of nuclear signals in a regular Butterworth filter. Compared with the traditional triple-pole filtering circuitry, the circuitry of this conditioner is more compact and flexible. Moreover, its output waveform is more symmetrical and the signal-to-noise ratio (SNR) is higher. The improvement in the resolution of spectrometer is also significant.

Key words Digital nuclear spectrometer, Pole-zero compensation, Butterworth filter

CLC numbers TL817, TN79^{+}2

1 Introduction

A traditional multichannel analyzer based on nuclear spectrometer systems have been developed for digitalized systems. Fig. 1 shows a type of high- resolution system termed as the unattached digitalized nuclear spectrometer system (UDNSS), which has been widely investigated and applied [1, 2].

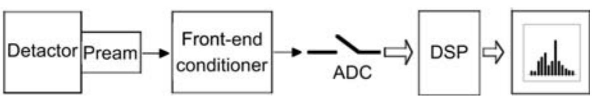

Fig. 1 The structure of UDNSS.

The main advantages of this circuit include no specific requirements for ADC sampling rates, simplified structures, and easy realization. However, regular ADCs with limited sampling frequency and dynamic range prevent the nuclear spectrometer from achieving high resolution. Therefore, a front-end conditioner is introduced in the digitalized systems. The conditioner critically pretreats output signals from the preamplifier. Hence, a high-energy resolution could be attained even for inputs at high counting rates and with large dynamic range.

The front-end conditioner has two basic functions. First, it shapes outputs with long exponential attenuating tail that come from the preamplifier into narrow pulses with optimum waveform. Saturation of ADC can be avoided during the overlapping of pulses. Thus, it is possible to modify the system's resolution. Second, a low-pass filter is used to limit the maximum

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frequency of signals in the frequency domain, which follows the principle of Nyquist sampling, realizing anti-aliasing of frequency. The pretreated signals are sent to the ADC for digitalizing, and then handled by a digital signal processing (DSP) system. Therefore, a high resolution of nuclear-energy spectrum can be obtained.

This article discusses the characteristics of nuclear signals in time domains and frequency domains. A novel type of front-end conditioner is proposed to better optimize the performance of the UDNSS and enhance the system's energy resolution. The composition of the conditioner, the characteristics of impulse response, and the realizing method are also described. The wave shapes and the results of energy spectra measurement are also dealt with in this study.

2 Characteristics of nuclear signals

In measuring systems of nuclear energy spectra, a sensing part usually contains a detector and a charge-sensitive preamplifier. A general charge-sensitive preamplifier is of a resistive feedback type. The output signal $V_i(t)$ is an exponential signal function with a fast-rising edge and a long tail. For easy analysis, the signal $V_i(t) = U(e^{-t/\tau_f} - e^{-t/\tau_r})$ is scale-normalized and can be estimated as [3]:

$$V_i(t) = e^{-t/\tau_f} \tag{1}$$

where τ_r is rise time constant and τ_f is fall-time constant of the biexponential signal.

The equation of frequency domain is:

$$V_i(s) = \frac{1}{s + \dfrac{1}{\tau_f}} \tag{2}$$

For reducing the impulse's tail lumping and preventing ADC saturation under high count rates, a pole-zero compensation (P/Z compensation) technique is used to obtain short tail-signals. For this, a transfer function can be composed [4]:

$$H_1(s) = \frac{s + \dfrac{1}{\tau_f}}{s + \dfrac{1}{\tau_p}} \tag{3}$$

where $\dfrac{1}{\tau_p}$ is the new pole.

After $H_1(s)$ acts on $V_i(s)$, a complete P/Z compensation can be realized. The output signal in frequency domain is expressed by

$$V_1(s) = \frac{1}{s + \dfrac{1}{\tau_p}} \tag{4}$$

And the formula of time domain of $V_1(s)$ is

$$V_1(t) = k_1\, e^{-t/\tau_p} \tag{5}$$

Under the complete realization of P/Z compensation, $\delta(t)$ can be considered as a signal passing through a filtering network of $1/(s + \Omega_p)$, in which Ω_p equates $1/\tau_p = 2\pi f_p$.

It is necessary to add several poles after the P/Z compensation network to realize wave filtering. Theoretically, as the number of poles of a filter increases, its impulse will be closer to the shape of the optimized filter. Hence, there will be an improvement in the SNR of treated signals. A current method is adding several real mutiple poles or conjugate complex poles [3].

The frequency response of a low-pass filter with *m* real poles is

$$H_{\text{r-pole}}(s) = \frac{1}{\tau^m (s + 1/\tau)^m} \tag{6}$$

and the frequency response of a filter with *n* complex poles is

$$\begin{aligned} H_{\text{c-pole}}(s) = {} & \frac{1}{[s+(a_1+j\omega_1)][s+(a_1-j\omega_1)][s+(a_2+j\omega_2)]} \times \\ & \frac{1}{[s+(a_2-j\omega_2)]\ldots\ldots[s+(a_n+j\omega_n)][s+(a_n-j\omega_n)]} \\ = {} & \frac{k_1}{s+a_1-j\omega_1} + \frac{k_1^*}{s+a_1+j\omega_1} + \frac{k_2}{s+a_2-j\omega_2} + \\ & \frac{k_2^*}{s+a_2+j\omega_2} + \ldots\ldots + \frac{k_n}{s+a_n-j\omega_n} + \frac{k_n^*}{s+a_n+j\omega_n} \end{aligned} \tag{7}$$

Combining a complete P/Z compensation filter with a low-pass filter network, a $\delta(t)$ signal can be considered to pass through $(m+1)$ rank real-pole or $(2n+1)$ rank complex-pole low-pass filter. Therefore, output signal shapes are totally determined by impulse response of systems corresponding to Eqs. (6) and (7). The impulse response of $(m+1)$ rank real-pole filter can be written as

$$h_{\mathrm{real}}(t) = \frac{t^m}{m!\tau_{\mathrm{p}}^m} \mathrm{e}^{-t/\tau_{\mathrm{p}}} \tag{8}$$

And the impulse response of $(2n+1)$ rank complex-pole filter is

$$h(t) = k_1 \mathrm{e}^{-a_1 t} + 2|k_2|\mathrm{e}^{-a_2 t}\cos(\omega_2 t + \theta_2) + \ldots\ldots + 2|k_n|\mathrm{e}^{-a_n t}\cos(\omega_n t + \theta_n) \tag{9}$$

where $k_n = |k_n|\mathrm{e}^{j\theta_n} n$.

In digital nuclear measuring systems, triple real-pole filter circuitry is used to a larger extent. However, the design of complex-pole filter circuitry and its realization have been investigated.

3 Positioning poles in a front-end conditioner of a low-pass filter

When considering functions of a low-pass filter in the front-end conditioner, the complex-pole mounting in regular Butterworth design was modified. An improved Butterworth filter was obtained, which was more suitable for nuclear measurement systems. Butterworth filter's frequency response is shown in Eq. (10) [5]:

$$|H(j\omega)|^2 = \frac{1}{1+(\omega/\omega_{\mathrm{p}})^{2N}} \tag{10}$$

where ω_p is cut-off frequency and N is the order of filter.

Poles in regular N-rank Butterworth filter symmetrically distribute on the left side of the unit circle, referring to real axes as symmetrical axes. Two neighbor poles have a π/N central angle between them. The impulse response of a 5-order Butterworth filter is shown in Fig. 2 (b). It can be seen that there is a significant tailing of breadth-reducing vibration in the impulse response of 5-order Butterworth filter. This causes migration of the baseline because of lumping of impulse tailing under high count-rates, thereby decreasing resolution. Therefore, two pairs of complex-poles were repositioned while maintaining the basics of Butterworth filter. Pole distribution of 7-order Butterworth filter was fixed first. Five poles, far from an imaginary axis, were selected as poles of the improved 5-order filter. The impulse response curve of the improved 5-order Butterworth filter is shown in Fig. 2 (c). It can be seen that the tailing vibration of impulse response considerably diminished after 5-order Butterworth filter was improved. The symmetry of the wave shape is closer to the Gaussian shape than that of impulse response of triple real-pole filter as shown in Fig. 2 (a). Consequently, the improved Butterworth filter is better suited for nuclear measurement systems.

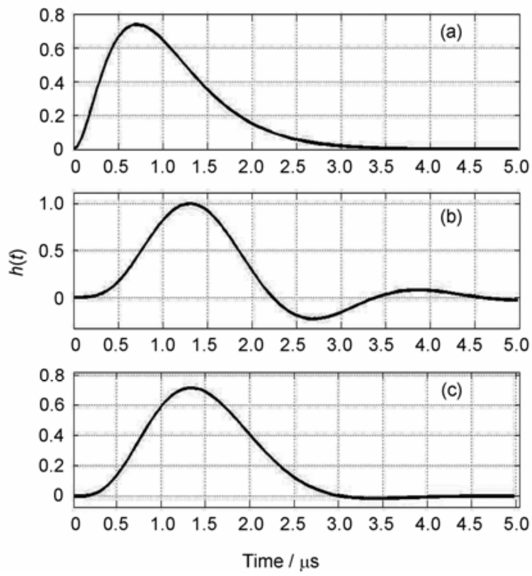

Fig. 2 Impulse response of various nets. (a) Triple real-pole net, (b) 5-order Butterworth net. (c) Modified 5-order Butterworth net.

4 Realization of circuitry and experimental results

A TDS3020B-type 300 MHz digital oscilloscope was used to observe signal waveform generated from a random signal generator at a sampling rate of 25 MHz (Fig. 3 (a)). The frequency characteristics of the signals are shown in Fig. 3 (b). According to the frequency characteristics, the triple real-pole front-end conditioner (Fig. 4(a)) and the improved 5-rank Butterworth circuits (Fig. 4(b)) were designed. The two circuits have the same cut-off frequency ($\Omega_{\mathrm{p}} = 2\pi\times 450\,\mathrm{kHz}$) and the same gain.

The signals as shown in Fig. 3 (a) were inputted to the two types of circuits as shown in Figs. 4 (a) and (b), respectively. The output signals obtained at a sampling rate of 500 MHz are shown in Figs. 5 (a) and (b). Comparing the results, it was found that the impulse width of the output signals from the 5-order Butterworth circuit and the triple real-pole circuit were 2.8 μs and 4.2 μs, respectively. The ratio of t_R (the right half width at half height of the impulse peak value) to t_L (the left half-width at that) was used to express the symmetry of the waveform. The two waveforms as shown in Figs. 5 (a) and (b) have a t_R / t_L value of 1.4 and 1.1, respectively. It is indicated that waveform (b) has better symmetry and narrower impulse width than (a).

Theoretically, the more symmetrical the impulse response of a physically realizable optimum filter, the higher will the SNR be and the narrower its width, the smaller will be its impulse lumping effect. All of these aid in increasing the resolution of the spectra.

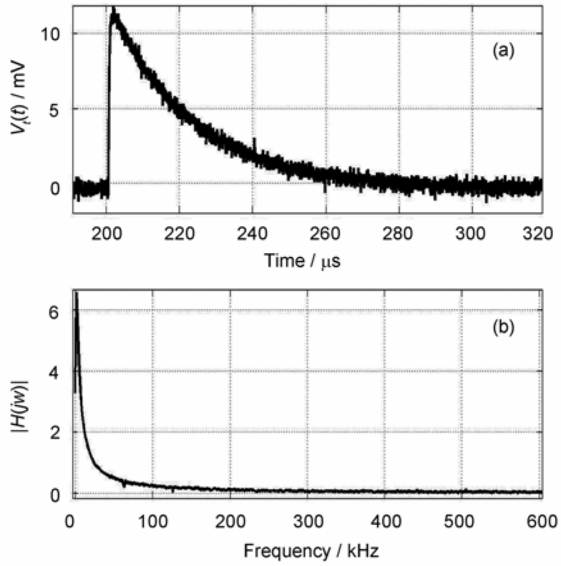

Fig. 3 (a) Waveform of input signal, (b) Frequency characteristic of input signals.

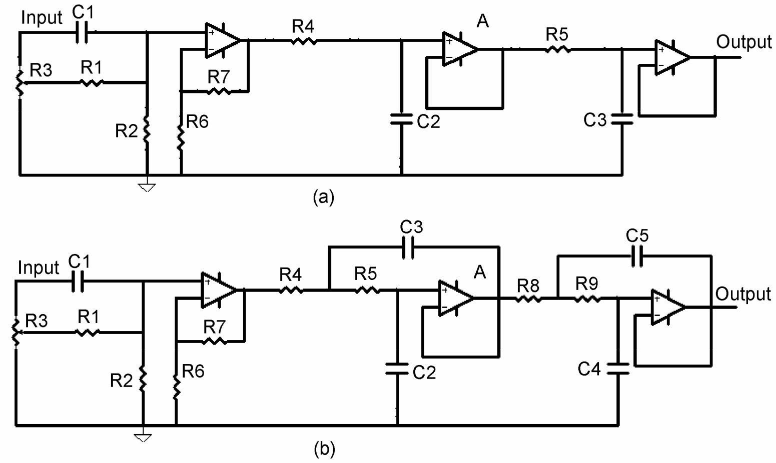

Fig. 4 (a) The triple real-pole filter circuit, (b) The modified 5-order Butterworth filter circuit.

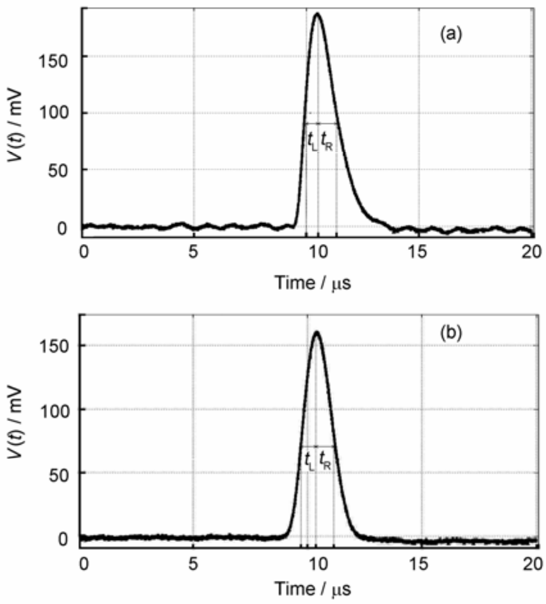

Fig. 5 (a) Output waveforms of the triple real-pole filter circuit, (b) Output waveform of the modified 5-order Butterworth filter circuit.

5 Conclusions

According to the theoretical analysis and experimental results, it can be concluded that:

1) The designed front-end conditioner of the digital spectrometer can effectively narrow the output signal width, enlarge the amplitude of the signal, and make the output signal match the following ADC;

2) The proposed improved 5-order Butterworth filter can resolve the aberration of signal in regular 5-order Butterworth filters, which is better suitable for digital nuclear spectrum measurement systems;

3) Compared to regular triple real-pole filters, the impulse response of the modified 5-order Butterworth filter (described in this article) is closer to the Gaussian shape and has better SNR;

4) More poles are obtained from the designed complex-pole-powered filter using fewer parts and less enlarging rank. The formed shapes maintain better quasi-Gaussian shape.

In brief, a satisfying impulse response can be achieved by adjusting the pole positions during the designing of complex-pole filters. Therefore, complex-pole filters have better flexibility than real-pole filters in practical application.

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