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A pulse-shape discrimination method for improving Gamma-ray spectrometry based on a new digital shaping filter

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ABSTRACT

It is a usual practice for improving spectrum quality by the mean of designing a good shaping filter to improve signal-noise ratio in development of nuclear spectroscopy. Another method is proposed in the paper based on discriminating pulse-shape and discarding the bad pulse whose shape is distorted as a result of abnormal noise, unusual ballistic deficit or bad pulse pile-up. An Exponentially Decaying Pulse (EDP) generated in nuclear particle detectors can be transformed into a Mexican Hat Wavelet Pulse (MHWP) and the derivation process of the transform is given. After the transform is performed, the baseline drift is removed in the new MHWP. Moreover, the MHWP-shape can be discriminated with the three parameters: the time difference between the two minima of the MHWP, and the two ratios which are from the amplitude of the two minima respectively divided by the amplitude of the maximum in the MHWP. A new type of nuclear spectroscopy was implemented based on the new digital shaping filter and the Gamma-ray spectra were acquired with a variety of pulse-shape discrimination levels. It had manifested that the energy resolution and the peak-Compton ratio were both improved after the pulse-shape discrimination method was used.

1. Introduction

For more than two decades, advancements in Digital Pulse Processing (DPP) have made it one of the most utilized techniques in development of digital nuclear spectroscopy (Jordanov, 2016). A nuclear particle detector often generates an EDP which is caused by a nuclear particle. After the DPP is performed, the EDP can be transformed into another pulse shape, such as a trapezoidal pulse (Regadío et al., 2014), a bipolar trapezoidal pulse (Esmaeili-sani et al., 2012), a bipolar triangular pulse shaping (Esmaeili-sani et al., 2011), a Gaussian pulse shaping (Chen et al., 2009; Chen et al., 2008), among others. The DPP is usually called as pulse shaping filter and the signal-noise ratio is improved during the processing.

Though the signal-noise ratio is improved after the EDP being transformed into another pulse shape, perhaps the pulse amplitude is calculated incorrectly as a result of pulse's baseline drifting (Xu et al., 2015), or bad pulses being mixed in the good pulses. The shape of the bad pulse is often distorted as a result of abnormal noise, unusual ballistic deficit or bad pulse pile-up. A good DPP should remove the effects of baseline drifting, or discriminate the pulse-shape and discard the distorted pulse as well. In the neutron detector, the width of the pulse output from the preamplifier is not the same as when the pulse is caused by gamma and neutron particles (Zaitseva et al., 2013). Such particles can be discriminated and selected based on the pulse width parameter (Alharbi, 2016; Zhang et al., 2012; Asztalos et al., 2016; Balmer et al., 2015). Wavelet transform had been used to discriminate the pulses caused by a variety of nuclear particles (Yousefi et al., 2009). Inspired by this, based on the pulse-shape discrimination, discarding the distorted pulse, designing this type of Gamma-ray Spectrometry and acquiring the Gamma-ray Spectra, the Spectra quality perhaps would be improved.

2. Method

Fig. 1 shows the schematic diagram of the spectra acquisition chain. The EDP generated in a nuclear particle detector is amplified and converted into a digital one. Then the digital EDP is transformed into a MHWP with the MHWP shaping filter. The Multi-channel analyzer obtains the MHWP's height and constructs the spectra at last. Meanwhile the bad pulse-shape is discriminated and the distorted pulse is discarded.

The MHWP-shape can be represented easily with some parameters and the distorted pulse can be discriminated with the parameter values. As shown in Fig. 2, the amplitude of the maximum H in the MHWP is

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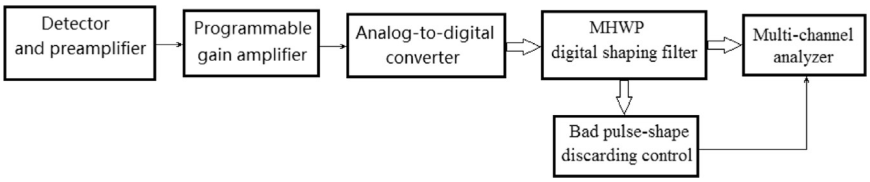

Fig. 1. Schematic diagram of the spectra acquisition chain.

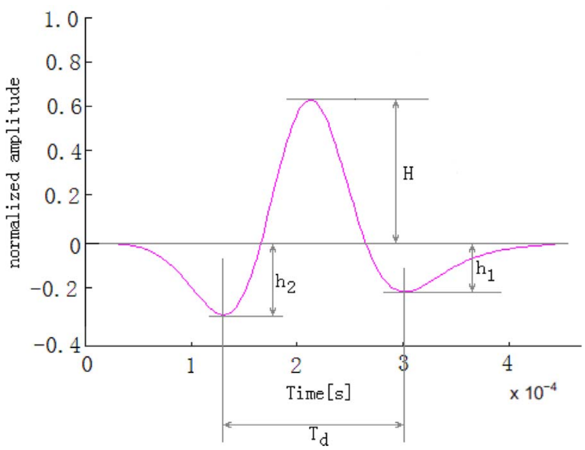

Fig. 2. MHWP-shape parameters represented with the $\frac{h_1}{H}$, $\frac{h_2}{H}$ and T_d.

the amplitude of the EDP caused by a nuclear particle. The MHWP-shape can be measured with the ratios $\frac{h_1}{H}$ and $\frac{h_2}{H}$, which are from the amplitudes of the two minima h_1 and h_2 respectively divided by the amplitude of the maximum H. The time difference T_d between the two minima can be also used to measure the MHWP-shape. If abnormal noise, unusual ballistic deficit or bad pulse pile-up appeared in the EDP, then the parameters $\frac{h_1}{H}$, $\frac{h_2}{H}$ and T_d would exceed the normal levels after the EDP was transformed into the MHWP.

Unlike Mexican hat wavelet transform applied in Gamma-ray Spectrometry as described in the literature (El Badri, et al., 2013), the MHWP shaping filter is a new digital shaping filter, which can transform an EDP into a MHWP. The impulse response of the filtering system should be deduced and a special-purpose digital logic circuit to process the filtering algorithm in real-time should also be designed.

3. Pulse shaping filter designing

It was assumed that when a particle is detected, the preamplifier stage will generate the following pulse:

$$x(t) = H\exp\left(-\frac{t}{\tau_0}\right)u(t) \tag{1}$$

where H is the pulse amplitude, τ_0 is the exponential decaying time constant, and $u(t)$ is the unit step function defined as follows:

$$u(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \tag{2}$$

The impulse response $h(t)$ is given by the following expression:

$$h(t) = \left[\frac{t^3}{s^4} - \frac{3t}{s^2} + \frac{1}{\tau_0}\left(1 - \frac{t^2}{s^2}\right)\right]\exp\left(-\frac{t^2}{2s^2}\right) \tag{3}$$

where s is the scale factor in the wavelet transform.

The transformation of an input signal x(t) into an output signal y(t) by a Linear Time-Invariant (LTI) system is mathematically expressed as the output signal as a convolution of the input signal and the impulse response of the system. The convolution is commonly written using the star (*) symbol. y(t) is given by the following expression:

$$y(t) = x(t)*h(t) = Hg\left(\frac{t}{s}\right) \tag{4}$$

where H is the pulse amplitude as shown in Eq. (1), s is the scale factor as shown in Eq. (3), and g(t) is a mother wavelet, namely defined as follows:

$$g(t) = (1 - t^2)\exp\left(-\frac{t^2}{2}\right) \tag{5}$$

The EDP, the impulse response and the output response of the system are depicted in Fig. 3.

Eq. (4) shows an important concept, which is deduced using the following formulas.

The property of the Fourier transform will be used in the following proof.

$$\text{if } f(t) \leftrightarrow F(\omega), \text{ then } \frac{d^n f(t)}{dt^n} \leftrightarrow (j\omega)^n F(\omega) \tag{6}$$

$$\text{if } f(t) \leftrightarrow F(\omega), \text{ then } f\left(\frac{t}{a}\right) \leftrightarrow aF(ja\omega)(a > 0) \tag{7}$$

The Fourier transform of a Gaussian signal will be used as well.

$$f(x) = \exp\left(-\frac{t^2}{2}\right) \leftrightarrow F(\omega) = \sqrt{2\pi}\exp\left(-\frac{\omega^2}{2}\right) \tag{8}$$

The wavelet basis function of g(t) convolution type is given by

$$g_s(t) = \frac{1}{s}g\left(\frac{t}{s}\right) \tag{9}$$

The derivative of g(t) is given by

$$\psi(t) = \frac{dg(t)}{dt} = (t^3 - 3t)\exp\left(-\frac{t^2}{2}\right) \tag{10}$$

The $\psi(t)$ in Eq. (10) is from the third derivative of $-\exp\left(-\frac{t^2}{2}\right)$. The Fourier transform of $\psi(t)$ is obtained with the Eqs. (6) and (8), as follows:

$$\hat{\psi}(\omega) = \sqrt{2\pi}j\omega^3\exp\left(-\frac{\omega^2}{2}\right) \tag{11}$$

The admissibility condition of a wavelet mother function is given by

$$C_\psi = \int_{-\infty}^{+\infty}\frac{|\hat{\psi}(\omega)|^2}{|\omega|}d\omega = 0 \tag{12}$$

$\psi(t)$ can be used as the wavelet mother function if $C_\psi < \infty$. The wavelet basis function of $\psi(t)$ convolution type is given by