New Methods to Remove Baseline Drift in Trapezoidal Pulse Shaping (Postprint)

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Abstract

Trapezoidal pulse shaping algorithm is widely applied to improve signal-to-noise ratio (SNR), throughput and energy resolution with the properties of noise suppression, pile-up pulse separation and ballistic deficit correction. The algorithm can be acquired by z transform method which is easier for derivation. However, the baseline drift of trapezoidal pulse appears because the noise superimposes on the input signal. In this paper, two new methods based on convergence analysis and noise suppression are proposed to remove the baseline drift resulting from trapezoidal pulse shaping. Simulations and experimental tests are carried out to verify the methods. The results demonstrate that the proposed methods can remove baseline drift in trapezoidal pulse shaping.

Full Text

Preamble

New Methods to Remove Baseline Drift in Trapezoidal Pulse Shaping

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Abstract: The trapezoidal pulse shaping algorithm is widely applied to improve signal-to-noise ratio (SNR), throughput, and energy resolution due to its properties of noise suppression, pile-up pulse separation, and ballistic deficit correction. The algorithm can be derived using the z-transform method, which facilitates derivation. However, baseline drift appears in the trapezoidal pulse because noise superimposes on the input signal. This paper proposes two new methods based on convergence analysis and noise suppression to remove the baseline drift resulting from trapezoidal pulse shaping. Simulations and experimental tests verify the methods. The results demonstrate that the proposed methods can effectively remove baseline drift in trapezoidal pulse shaping.

Keywords: Baseline drift removal, Trapezoidal pulse shaping, z-transform method
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Introduction

Digital pulse shaping algorithms constitute a primary focus of digital spectrometers. These algorithms are implemented in field programmable gate arrays (FPGA) to realize pulse shaping. The trapezoidal pulse, with its rise time equal to its fall time, provides a near-optimum signal-to-noise ratio (SNR). The flat top of the trapezoidal pulse can be flexibly set to adapt to different measurement conditions. Consequently, the trapezoidal pulse shaping algorithm is widely applied to improve SNR, throughput, and energy resolution.

The theory of trapezoidal pulse shaping has been well developed and documented in the literature. Radeka designed a trapezoidal filter based on a gated filter system, which achieved good resolution with large germanium detectors at high counting rates and higher energies [**?**]. Jordanov et al. developed the recursive algorithm for trapezoidal pulse shaping using a convolution method [**?**, **?**]. This convolution-based algorithm made trapezoidal pulse shaping feasible through digital means. Stein et al. employed a moving window deconvolution technique to realize trapezoidal and triangular shaping in digital systems [**?**]. Additionally, a real-time digital signal processor (DSP) pulse shaper synthesized by concave and convex pulse shapes was implemented in programmable logic [**?**]. Cosimo Imperiale also described the z-transform method for obtaining the recursive algorithm of trapezoidal pulse shaping [**?**], with subsequent simulations discussed in the literature \cite{7-10}. Recently, the trapezoidal shaper has been employed in digital spectrometers for ballistic deficit correction, neutron-gamma discrimination, and pile-up correction [**?**, **?**]. Furthermore, typical shapers—including triangular, trapezoidal, and cusp-like shapes—were generated in a new adaptive digital shaper that enabled automatic adjustment of coefficients for shaping an input signal [**?**].

However, when the input signal contains noise, baseline drift appears in the trapezoidal pulse, becoming particularly evident during the processing of consecutive pulses. This paper proposes two methods to remove this baseline drift. The feasibility and accuracy of these methods are verified through simulations and experiments. The results show that the methods can effectively remove baseline drift in trapezoidal pulse shaping.

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Trapezoidal Pulse Shaping

The trapezoidal pulse shaping algorithm was developed using the z-transform method [?]. As shown in Fig. 1 [Figure 1: see original paper], a trapezoidal pulse can be directly synthesized by Eq. (1):

$$v_o(t) = \sum_{i=1}^{4} v_i(t),$$

where $v_1(t) = (V_{\max}/t_a) \cdot tu(t)$, $v_2(t) = -v_1(t - t_a)u(t - t_a)$, $v_3(t) = -v_1(t - t_b)u(t - t_b)$, and $v_4(t) = v_1(t - t_c)u(t - t_c)$. Here, t_a is the rise time of the trapezoidal pulse, $t_b - t_a$ is the duration of the flat top, t_c is the total pulse width, and $V_{\max}$ is the pulse height.

Equation (1) can be expressed as Eq. (2) according to the z-transform:

$$V_o(z) = \frac{V_{\max} z(1 - z^{-n_a} - z^{-n_b} + z^{-n_c})}{n_a(1 - z^{-1})^2},$$

where $n_a = t_a/T_s$, $n_b = t_b/T_s$, $n_c = t_c/T_s$, and T_s is the ADC sampling time. The input signal is defined as $v_i(t) = Ae^{-t/\tau}u(t)$ for $t \geq 0$, where A is the height and τ is the time constant. The z-transform of the input signal is:

$$V_i(z) = \frac{A}{1 - dz^{-1}},$$

where $d = e^{-T_s/\tau}$. The transfer function can be represented as:

$$H(z) = \frac{V_o(z)}{V_i(z)} = \frac{(1 - dz^{-1})(1 - z^{-n_a})(1 - z^{-n_b})z^{-1}}{n_a(1 - z^{-1})^2}.$$

This yields:

$$V_o(z)(1 - z^{-1})^2 = V_i(z) \cdot \frac{(1 - dz^{-1})(1 - z^{-n_a})(1 - z^{-n_b})z^{-1}}{n_a}.$$

Applying the inverse z-transform gives the time-domain output v_o:

$$v_o[n] = 2v_o[n-1] - v_o[n-2] + \frac{1}{n_a}\{v_i[n-1] - v_i[n-n_a-1] - v_i[n-n_b-1] + v_i[n-n_c-1] - d\cdot[v_i[n-2] - v_i[n-n_a-2] - v_i[n$$

with $v_o[n] = v_i[n] = 0$ for $n \leq 0$.

Letting $y[n] = v_o[n]$ and $x[n] = v_i[n]$, Eq. (7) can be written as:

$$y[n] = 2y[n-1] - y[n-2] + X[n],$$

where

$$X[n] = \frac{1}{n_a}\{x[n-1]-x[n-n_a-1]-x[n-n_b-1]+x[n-n_c-1]-d\cdot[x[n-2]-x[n-n_a-2]-x[n-n_b-2]+x[n-n_c-2]]\}.$$

The recursive equations of Eq. (8) are:

$$\begin{aligned}
y[n]-y[n-1] &= y[n-1]-y[n-2]+X[n],\\
y[n-1]-y[n-2] &= y[n-2]-y[n-3]+X[n-1],\\
y[n-2]-y[n-3] &= y[n-3]-y[n-4]+X[n-2],\\
&\vdots\\
y[3]-y[2] &= y[2]-y[1]+X[3],\\
y[2]-y[1] &= y[1]-y[0]+X[2].
\end{aligned}$$

Accumulating these equations yields an expression relating $y[n]$, $y[n-1]$, $y[1]$, $y[0]$, and $X[n]$:

$$y[n]-y[n-1] = y[1]-y[0]+\sum_{i=2}^{n} X[i].$$

The trapezoidal pulse shaping is implemented using Eq. (7), which is suitable for processing ideal input signals without noise. However, input signals are generally superimposed with Gaussian white noise. An input signal with SNR = 30 dB was simulated using Eq. (3) with $A = 2000$ and $\tau = 100$. The result of trapezoidal pulse shaping with $n_a = 150$, $n_b = 300$, $n_c = 450$, and $T_s = 1$ is shown in Fig. 2 [Figure 2: see original paper]. The baseline drift of the trapezoidal pulse appears when the input signal contains Gaussian white noise. Simulation results indicate that lower SNR leads to more serious baseline drift.

Simulations and Experimental Tests

Convergence Conditions

The general formula for $y[n]$ is:

$$y[n]-y[1] = (n-1)(y[1]-y[0])+\sum_{i=2}^{n} X[i]+\sum_{i=2}^{n-1}\sum_{j=2}^{i} X[j].$$

Figure 2 shows that the algorithm based on the z-transform method is not convergent. To remove the baseline drift, a new method based on convergence analysis is employed. Assuming $y[0] = y[1] = 0$, Eq. (9) can be simplified to Eq. (10):

$$y[n] = \sum_{i=2}^{n} X[i] + \sum_{i=2}^{n-1} \sum_{j=2}^{i} X[j].$$

The discrete input signal $v_i[n]$ forms a geometric progression with ratio $q = e^{-1/\tau}$. It can be proved that $X[n]$ is also a geometric progression with the same ratio q. Equation (10) can then be expressed as:

$$y[n] = X[2] + X[2]\frac{1-q^2}{1-q} + \cdots + X[2]\frac{1-q^{n-2}}{1-q} + X[2]\frac{1-q^{n-1}}{1-q}.$$

Let $y[n] = X[2] + Y$, where $Y = C \cdot (1-q^2) + \cdots + C \cdot (1-q^{n-2}) + C \cdot (1-q^{n-1})$, with $C = X[2]/(1-q)$. Then:

$$Y = C\left[n - 2 - \frac{q^2(1-q^{n-2})}{1-q}\right].$$

Since $q < 1$ when $\tau > 1$, $y[n]$ can converge when $Y = 0$. From Eqs. (8) and (12), Y can be set to 0 by setting $x[1] = 0$. Figure 3 [Figure 3: see original paper] illustrates the result of trapezoidal pulse shaping with $v_i[1] = 0$, using the same input signal as in Fig. 2. Output 1 is provided for comparison, while Output 2 shows the trapezoidal pulse with the first input data set to 0. This demonstrates that the new method can remove baseline drift resulting from trapezoidal pulse shaping.

Noise Suppression

The baseline drift in trapezoidal pulse shaping is caused by noise accumulation. Filtering the original signal before shaping provides another approach to removing baseline drift. The digital S-K filter performs well in signal processing, offering both amplitude and frequency filtering capabilities [**?**]. The true height of the filtered signal can be obtained by properly adjusting the amplitude filtering factor.

The digital S-K filter algorithm is:

$$y[n] = \frac{(k \cdot (3-a) + 2k^2) \cdot y[n-1] - k^2 \cdot y[n-2] + a \cdot x[n]}{1 + k \cdot (3-a) + k^2},$$

with $y[n] = x[n] = 0$ for $n \leq 0$, where $x[n]$ is the discrete input signal, $y[n]$ is the output signal, k is the frequency filtering factor, and a is the amplitude filtering factor.

The original signal from Fig. 2 is filtered using the digital S-K filter, and the filter output is processed recursively using Eq. (7). The baseline drift of the trapezoidal pulse is removed with $k = 5$ and $a = 1.15$, as shown in Fig. 4 [Figure 4: see original paper].

Differential operation can also attenuate noise. Equation (6) can be rewritten as:

$$V_o(z) = \frac{V_i(z)}{(1-1/z)^2} \cdot \frac{(1-dz^{-1})(1-z^{-n_a})(1-z^{-n_b})z^{-1}}{n_a}.$$

Assuming $V(z) = V_i(z)/(1-1/z)^2$, an improved recursive algorithm for trapezoidal pulse shaping is obtained:

$$v[n] = 2v[n-1] - v[n-2] + v_i[n],$$
$$v_o[n] = \frac{1}{n_a}\{v[n-1] - v[n-n_a-1] - v[n-n_b-1] + v[n-n_c-1] - d \cdot (v[n-2] - v[n-n_a-2] - v[n-n_b -$$

with $v_o[n] = v[n] = 0$ for $n \leq 0$.

Equation (15) represents the improved recursive algorithm for trapezoidal pulse shaping without baseline drift [**?**]. The trapezoidal pulse can be implemented using Eq. (15), and Fig. 5 [Figure 5: see original paper] demonstrates that the improved algorithm can remove the baseline drift observed in Fig. 2.

Measured Pulse Shaping

To verify the feasibility of the proposed methods, experimental pulse tests were conducted. Pulses with a time constant of 3.2 µs were detected by a silicon drift diode (SDD) detector and digitized by an ADC at 20 MSPS, yielding $T_s = 50$ ns and $\tau = 3.2$ µs according to Eq. (7). A trapezoidal pulse with $t_a = 4$ µs, $t_b = 4$ µs, and $t_c = 8$ µs (corresponding to $n_a = 80$, $n_b = 80$, and $n_c = 160$) was implemented using Eqs. (7) and (15). The experimental results for different methods are presented in Fig. 6 [Figure 6: see original paper].

The results indicate that both the new method and the improved recursive algorithm can effectively remove baseline drift in trapezoidal pulse shaping. While the digital S-K filter can also be used for signal filtering to remove baseline drift, it is complex to implement in FPGA, and selecting appropriate values for k and a is challenging. Therefore, the new method and the improved recursive algorithm are recommended for practical applications. The correlation between the new method and the improved recursive algorithm is shown in Fig. 7 [Figure

7: see original paper], demonstrating that the improved method is suitable for trapezoidal pulse shaping without baseline drift.

Conclusion

This paper derives the recursive algorithm for trapezoidal pulse shaping using the z-transform method and discusses approaches to baseline drift removal. Setting the first input data to 0 and employing the digital S-K filter effectively remove baseline drift caused by noise accumulation. Experimental test results demonstrate that these methods can eliminate baseline drift in trapezoidal pulse shaping. A comparison between the new method and the improved recursive algorithm reveals a good linear relationship between them. The new method is recommended for real-time trapezoidal pulse shaping applications.

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