Improvement of Digital S-K Filter and Its Application in Nuclear Signal Processing Postprint

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

Abstract

On the basis of preliminary studies, a novel duo-parameter model consisting of amplitude filter factor and frequency filter factor for low-pass S-K filter is presented in this paper. The model is established by applying numerical differentiation method. Some simulation experiments and real data tests are carried out to verify the feasibility and superiority of the new algorithm. The results show that this duo-parameter model of low-pass S-K filter can be used to achieve high performance in signal processing and nuclear spectrum smoothing.

Full Text

Preamble

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Abstract

Based on preliminary studies, this paper presents a novel duo-parameter model for low-pass S-K filters comprising an amplitude filter factor and a frequency filter factor. The model is established using numerical differentiation methods. Simulation experiments and real data tests are conducted to verify the feasibility and superiority of the proposed algorithm. Results demonstrate that this duo-parameter model of low-pass S-K filter achieves high performance in signal processing and nuclear spectrum smoothing.

Key words
Digital S-K Filter, Duo-parameter Model, Numerical Differential, Nuclear Spectrum Smoothing

Introduction

Digital filters are implemented in many practical forms, broadly categorized into finite impulse response (FIR) and infinite impulse response (IIR) types. Both categories can be realized in hardware and software. Hardware implementations typically consist of adders, multipliers, and other functional units, contrasting with analog filters composed of resistors, inductors, and capacitors [1,2]. Generally, digital signal processing systems are readily realized using digital integrated circuits, offering advantages of compact size, high stability, and programmability. Alternatively, digital filters can be implemented in software based on theoretical algorithms executed by digital computers [3 7].

The S-K filter is a common active-filter circuit introduced by R. P. Sallen and E. L. Key in 1955 [1,2]. Analog S-K filters are widely employed in nuclear signal shaping. Early nuclear spectrum smoothing predominantly utilized multi-point smoothing methods. In recent years, numerous new data smoothing approaches have emerged, including FFT transformation, Kalman filtering, and wavelet transformation [8 18]. In preliminary research, nuclear pulse signals were shaped digitally in real-time using digital S-K filters [19,20]. This paper extends that work to nuclear spectrum data processing. First, the digital S-K filter is established by incorporating a signal gain control unit. Second, both general signals and spectrum data are simulated using the new filter. Finally, the feasibility of the proposed filter is verified by comparing results with different smoothing methods.

2 S-K Filter

Two representative S-K filter circuits exist: high-pass and low-pass configurations. Due to positive feedback control, these filters exhibit a large quality factor. When applied to nuclear pulse signal shaping, Gaussian waveforms can be obtained with relatively low filter order [20].

[Figure 1: see original paper]

2.1 Numerical Analysis Implementation of S-K Filter

In preliminary studies, signal amplitude amplification was observed following digital shaping with the basic S-K filter. The algorithms are given in Eq.(1) and Eq.(2). The data processing results are shown in Fig.2.

In the circuit of Fig.1, resistors R1 and R2 and capacitors C1 and C2 are designed to have identical values. Substituting Eq.(7) into Eq.(3), Eq.(4), and Eq.(6) yields simplified expressions that can be rewritten as Eq.(8). Through formal transformation, Eq.(8) becomes Eq.(9). Based on the numerical differential method, Eq.(9) can be further transformed, leading to Eq.(10) and subsequently Eq.(12). Under certain assumptions, Eq.(11) can be expressed as Eq.(12).

[Figure 2: see original paper]

To adapt the S-K filter for general digital signal processing, it must be established through numerical analysis with careful consideration of amplitude factors. Four nodes are identified in Fig.1, with corresponding voltages marked as Vf, Vp, Vn, and Vo. Applying Kirchhoff' s Current Law yields four voltage transmission equations. Assuming certain conditions, Eq.5 can be rewritten as Eq.(7). Based on Eq.(12), the output yn can be described by Eqs.(13) and (14).

In summary, the output signal of digital Gaussian shaping can be achieved through recursive execution of Eqs.(13) and (14). The factors k and a play crucial roles in regulating the output signal: factor k is defined as the frequency filter factor, which adjusts the width of the output signal, while factor a is defined as the amplitude filter factor, which adjusts the amplitude of the output signal.

3 Application Study of Digital S-K Filter in Signal Processing

The digital S-K filter is suitable for real-time signal processing. In simulation experiments, a sinusoidal signal (amplitude range 1000) with a period of 360 points serves as the original signal. A noise signal with amplitude ranging from -100 to 100, generated using a random number generator in the VBA (Visual Basic for Applications) platform, is added to simulate the input signal. The optimal output signal with phase-shifting is obtained at filtering parameters k=25, a=1.15, as shown in Fig.3. The correlation analysis between the original signal and output signal is presented in Fig.4. Additional correlation analysis was performed on the output signal left-shifted by 45 points, with results shown in Fig.5.

[Figure 3: see original paper]
[Figure 4: see original paper]
[Figure 5: see original paper]

A numerical simulation experiment for detector output signals was conducted, improving upon the simulation results of Ref.[20]. In this experiment, a noise signal generated by a random number generator is added to a standard negative exponential signal to simulate real nuclear signals. This approach facilitates analysis of the digital S-K filter' s smoothing effect on noisy signals, with results shown in Fig.6. When the input signal-to-noise ratio is 10 dB, the output signal-to-noise ratio can exceed 30 dB using the digital S-K filter with parameters k=5, a=1.1.

[Figure 6: see original paper]

The smoothing effect is determined by both the smoothing factor and the spectrum resolution. A resolution experiment was conducted using an EDXRF software system with the digital S-K filter, employing Fe-55 as the radioactive source. The resulting spectrum is shown in Fig.7.

[Figure 7: see original paper]
[Figure 8: see original paper]

4 Application Study of Digital S-K Filter in Nuclear Spectrum Smoothing

Original spectra from nuclear instruments exhibit statistical fluctuations and are often superimposed with noise, necessitating spectrum data smoothing [21 28]. Historically, multi-point filters such as 5-point, 7-point, 9-point, and 11-point filters have been widely used. Recently, new smoothing methods have gained attention, including digital S-K filters, FFT filters, Kalman filters, and wavelet filters [29 33].

Using the digital S-K filter as an example, the filter factors k and a can be continuously optimized through computer simulation to obtain favorable values. The smoothing result of an original spectrum using the digital S-K filter is shown in Fig.7. A resolution experiment was performed using an EDXRF analyzer with a W target (20 kV, 50 A) and Si-PIN detector on a mixed sample (SiSCaTiFe). Quartic polynomial fitting curves corresponding to results from four filter types and the unfiltered case are shown in Figs.9–12. The smoothing factor for different methods, evaluated by comparing fitting data with measured data and denoted as R^2, is presented in Table 2.

It is difficult to implement Kalman and wavelet filters on hardware platforms; they are typically executed using software tools such as MATLAB and VBA. Therefore, resolution analysis typically compares data from digital S-K, FFT, 11-point, and 5-point filters with original detector data, while also comparing computational requirements. Table 3 compares peak positions obtained with different smoothing methods.

In summary, the spectrum smoothing factor improves after digital filtering, while resolution deteriorates—better smoothing factors correspond to worse resolution. Multi-point filters are widely used in spectrum processing software to achieve favorable resolution. However, the digital S-K filter uniquely offers both improved smoothing factor and maintained spectrum resolution, making it suitable for applications where spectrum resolution is not the highest priority.

All digital S-K filter data in Table 3 exhibit a two-channel backward deviation, differing from other smoothing methods. This data deviation arises from the characteristics of the digital S-K filter’ s iterative algorithm, which processes spectrum data from left to right. Algorithm improvement is the primary solution to rectify this deviation, involving three steps: left-shifting the filtered data by two channels, discarding the first two data points, and filling zeros in the last two channels.

[Figure 9: see original paper]
[Figure 10: see original paper]
[Figure 11: see original paper]
[Figure 12: see original paper]

5 Conclusion

A new digital S-K filter with two shaping factors has been established through analog S-K filter simulation and numerical analysis. Real-time signal processing tests verify that the new filter can be widely applied to data smoothing and real-time signal processing. Compared with other methods, introducing the digital S-K filter to nuclear spectrum data smoothing represents a successful innovation. In summary, the filter offers advantages in real-time nuclear spectrum data processing due to its simple algorithm, easy factor selection, and excellent results.

References

1. Wang J J, Fan T M, Qian Y G. Nuclear electronics. Beijing, Atomic Energy Press, 1983, 27-40 (in Chinese).
2. Wang Z Y, Lou B Q, Zhu J J, et al. Principle of Nuclear Electronics. Beijing, Atomic Energy Press, 1989, 102-118 (in Chinese).
3. Goulding F S. Nucl Instrum Methods, 1977, 142: 428-432.
4. Jordanov V T, Knoll G F. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1994, 345: 337-345.
5. Jordanov V T, Knoll G F, Huber A C. Nucl Instrum Methods Phys Res SectA: Accelerators, Spectrometers, Detectors and Associated Equipment, 1994, 353: 201-206.
6. Jordanov V T, Pantazis J A, Huber A C. Nucl Instrum Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1996, 380: 353-357.
7. Jordanov V T. Nucl Instrum Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2003, 505: 347-351.
8. Pullia G, Geraci A, Ripamonti G. Nucl Instrum Methods in Phys Res, Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2000, 439: 378-384.
9. Gatti E, Geraci A, Ripamonti G. Nucl Instrum Methods phys Res, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,

1998, 417: 111–117.

10. Gerardi G, Abbene L, La Manna A. IEEE Trans Nucl Sci, 2007, 571: 342–346.
11. Simoes P C, Veloso J F, DosSantos J M. IEEE Trans Nucl Sci, 1997, 44: 521–526.
12. Simoes P C, Martins J C, C.M. Correia C M, IEEE Trans Nucl Sci, 1996, 43: 1804–1809.
13. Emmanuel L, Fernando X N. Comput Electrical Eng, 2010, 36: 261–268.
14. Singh A K, Kumar P, Singh G, Digital Signal Processing, 2010, 20: 496–501.
15. Zhou J B, Zhou W, Fang F, et al. 2011 proceedings of the 10th ICEMI, 2011, 4: 163–165.
16. Mott R B. Nucl Instrum Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2010, 624: 265–269.
17. Syntfeld-Każuch, Sibczyński P, Moszyński M, et al, Radiat Measure, 2010, 45: 377–379.
18. Basappa S, Kerur B R, Anilkumar S, et al, Appl Radiat Isotop, 2010, 68: 76–83.
19. Menaa N, D' Agostino P, Jordanov V T, et al, Nucl Instrum Methods in Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2010, 44: 278–281.
20. Nakhostin M, Hitomi K, Ishii K, et al, Nucl Instrum and Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2010, 615: 345–351.
21. Fernandes A M, Pereira R C, Sousa J, et al, Fusion Eng Design, 2010, 85: 308–312.
22. Planche T, Fourrier J, Lancelot J L, et al, Nucl Instrum Methods in Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2009, 604: 540–544.
23. Gros S, Hammond N J, Lister C J, et al, Nucl Instrum Methods Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2009, 602: 386–390.
24. Noulis T, Deradonis C, Siskos S. Nucl Instrum Methods in Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2008, 589: 376–381.
25. Gerardi G, Abbene L, La Manna A. Nucl Instrum Methods in Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2007, 571: 342–346.

26. Noulis T, Deradonis C, Siskos S, et al, Nucl Instrum Methods in Phys Res Sect A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2006, 556: 231-235.

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