VHDL Simulation of Cusp-like Filter for High Resolution Radiation Spectroscopy

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Abstract- One of the main objectives of a radiation spectroscopy is to have good energy resolution so that the results of the nuclear physics experiments can be interpreted faithfully. Electronic noise introduced by the instrumentation systems put a major constraint on the energy resolution. It has been proved theoretically by many researchers/authors that the signal to noise ratio can be maximized to its best value if the electrical pulse obtained from a nuclear detector can be shaped into an infinite cusp form. Practically a cusp-like pulse of finite length can be obtained by processing the detector signals in digital domain. This paper considers VHSIC Hardware Description Language (VHDL) simulation aspect of cusp-like filtering algorithm. Such simulations provide the platform to verify the algorithms for their implementation into a digital hardware such as Field Programmable Gate Array (FPGA) for real time applications. The simulation considers exponentially decaying sequences as the input to the filter. In radiation spectroscopy applications, such signals are obtained by digitizing the slow decaying exponential pulses derived from radiation detectors.

Index Terms- Cusp-like Filter, Energy Resolution, Signal to Noise Ratio, Radiation Spectroscopy, VHDL.

I. Introduction

In a typical radiation spectroscopy, the ionizing radiation quantum interacts with the sensitive volume of a nuclear detector and releases its energy into the same. This process generates an equivalent charge which is further collected by the preamplifier to form a voltage pulse. Peak of a voltage pulse obtained from preamplifier carries important information as the same is proportional to energy of the radiation quantum. The capability of a spectrometer to distinguish radiation quantum closely separated in energy is characterized by its energy resolution [1].The energy resolution is a crucial parameter to interpret the findings of a nuclear physics experiment. A poor energy resolution gives rise to widening of spectral lines that may lead to wrong interpretation of the experiment. Energy resolution is usually given by Full width at Half Maximum (FWHM) of the spectral peaks when the detector pulse is approximated by the Gaussian shape [1].

$$FWHM = 2.35\sigma \qquad (1)$$

Where σ is the standard deviation of the Gaussian pulse.
In case of spectroscopy the system FWHM is given by the following relation,

$$FWHM^2_{system} = FWHM^2_{detector} + FWHM^2_{electronic} \qquad (2)$$

Where $FWHM^2_{detector}$ mainly depends on statistical fluctuations in charge carrier generation in detector due to discrete nature of radiation quantum. $FWHM^2_{electronic}$ depends on the noise contribution of preamplifier and other associated instrumentation. The noise introduced by used instrumentation can be termed as electronic noise and it mainly depends on DC baseline fluctuations, pulse pileup effects, electromagnetic and power supply disturbances [2]. Therefore to achieve the best energy resolution the noise must be minimized. Various theories have been established to maximize the signal to noise ratio [1],[3],[4].The amount of electronic noise is often expressed in terms of the equivalent noise charge (ENC). ENC is the amount of charge when applied to input of the instrumentation system, will result in output voltage equal to RMS (i.e. Root Mean Square) level of output due to noise only[1]. ENC can be decomposed into three terms: one proportional to current (or parallel) noise, another proportional to voltage (or series) noise and the last proportional to 1/f noise. Efficiency of various noise shaping filters are characterized by their ENC value. If an impulse signal is applied to a circuit having only current and voltage noise, the infinite cusp filter offers the best ENC value [5]. The modified versions of infinite cusp filter have extensively been considered in spectroscopy applications to shape the detector pulse in presence of all the three types of noise sources [6],[7]. Due to above mentioned reasons the infinite cusp has been considered as optimum detector pulse shape to achieve the best possible signal to noise ratio and same has become the standard for comparing the performance of other methods of pulse shaping. Figure 1 shows various pulse shapes and their signal to noise ratio relative to an infinite cusp. Practically it is very difficult, rather impossible to obtain the infinite cusp shape using analog circuit techniques [8]. However the digital signal processing techniques can be exploited to obtain a finite length cusp-like shape. Such shaping will improve the performance of a radiation spectrometer in terms of energy resolution by maximizing the signal to noise ratio. Additionally the same techniques can also minimize the pile up losses. This paper is organized as follows. Section II briefly describes the cusp-like filtering algorithm. It also briefly discusses the used methodology and heart of the developed simulation code. Section III discusses the simulation results. Finally, the concluding remarks are included in Section IV.

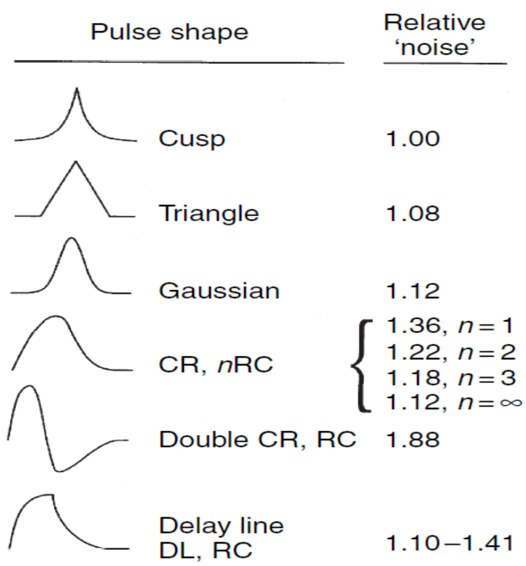

Figure 1: Noise contribution of different pulse shapes relative to infinite cusp (top).

II. CUSP-LIKE FILTERING ALGORITHM

The finite length cusp-like filtering algorithm can be described in its recursive form [9]. The recursive forms are often faster in execution and same can easily be implemented into digital hardware. The following recursive equations were considered for the VHDL simulation.

$$d\_K[i] = x[i] - x[i-K] \quad (3)$$
$$d\_1[i] = x[i] - x[i-1] \quad (4)$$
$$b[i] = d\_K[i] - K * d\_1[i-L], \ i \geq 0 \quad (5)$$
$$c[i] = b[i] + c[i-1], \ i \geq 0 \quad (6)$$
$$s[i] = M2 * c[i] + s[i-1], \ i \geq 0 \quad (7)$$
$$t[i] = M1 * c[i] + s[i], \ i \geq 0 \quad (8)$$
$$y[i] = t[i] + y[i-1], \ i \geq 0 \quad (9)$$

Where X[i] is digitized input exponential signal and Y[i] is output of the filter respectively. The value of M is given by the equation (10). The value of M1 and M2 can be selected to satisfy the equation (11). The symbol (*) in the above equations is a multiplication operator.

$$M = \frac{1}{e^{\left(\frac{T_p}{\tau}\right)} - 1} \quad (10)$$

$$M = \frac{M1}{M2} \quad (11)$$

Where T_p is digitizer's clock frequency and τ is time constant of exponential input signal. The duration of the rising (falling) edge of the cusp-like shape is decided by the value of L, and the value of K is equal to 2L+1. For high count applications a detector pulse is required to be processed to the short duration [10][11]. The short duration pulse of cusp-like shape can be obtained by appropriately choosing the value of L to minimize the pile up losses. Figure 2 is block diagram representation of the recursive equations given above. The nature of input signal considered for the simulation was similar as considered in our previous paper [12] and the same has been shown in figure 3. Heart of the simulation code is a 'generate statement' which instantiates the various components required for the filtering operation and the same is given below.

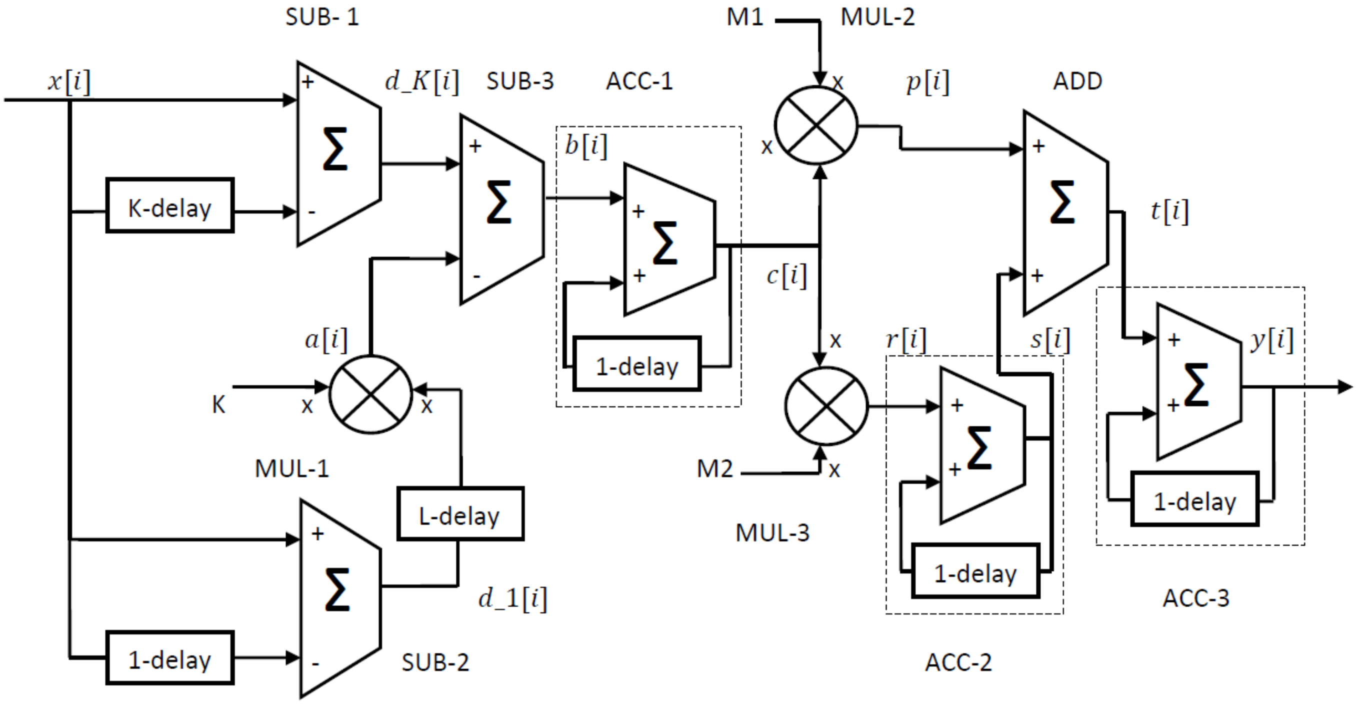

Figure 2: Block diagram of cusp-like filter

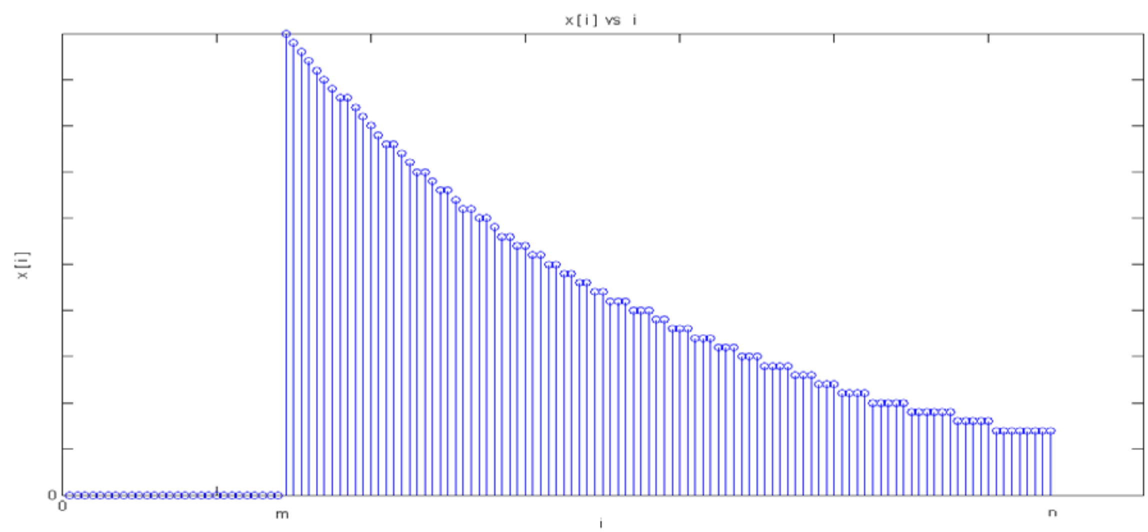

Figure 3: Input sequence to cusp-like filter

begin
Cusp-like filter : for i in m to n generate
SUB-1 : subtractor port map (x(i), x(i-K), d_K(i));
SUB-2 : subtractor port map (x(i), x(i-1), d_1(i));
MUL1 : multiplier port map (K, d_1(i-L), a(i));
SUB-3 : subtractor port map (d_K(i), a(i), b(i));
ACC-1 : adder port map (c(i-1), b(i), c(i));
MUL-2 : multiplier port map (M1, c(i), p(i));
MUL-3 : multiplier port map (M2, c(i), r(i));
ACC-2 : adder port map (s(i-1), r(i), s(i));

ADD : adder port map (s(i), p(i), t(i));
ACC-3 : adder port map (y(i-1), t(i), y(i));
end generate Cusp-like filter;

The filtering scheme comprises of three subtractors, three multipliers, three accumulators and an adder respectively. The subtractors (SUB-1, SUB-2 and SUB-3) and multipliers (MUL-1, MUL-2 and MUL-3) are generated by instantiating the components 'subtractor' and 'multiplier' respectively. Whereas the adder and accumulators are generated by instantiating the component 'adder'. The first two ‘signal’s in parentheses (after the keyword 'port map') for each component are mapped to input ports while the third ‘signal’ is mapped to output port respectively. All the ‘signal’s are one dimensional array of size 'n'.

III. Simulation Results

The simulations were performed for non-piled up input sequences as well as for piled up input sequences by considering different values of shaping parameters (i.e. K and L). Figure 4 shows the simulation result for single input sequence while the figure 5 shows the simulation result for piled up input sequence respectively. Both the figures show plots for x[i], c[i], t[i] and y[i] respectively. The value of L, K, M1, M2 and M was selected/calculated as 7, 15, 200, 4 and 50 respectively in both the cases.

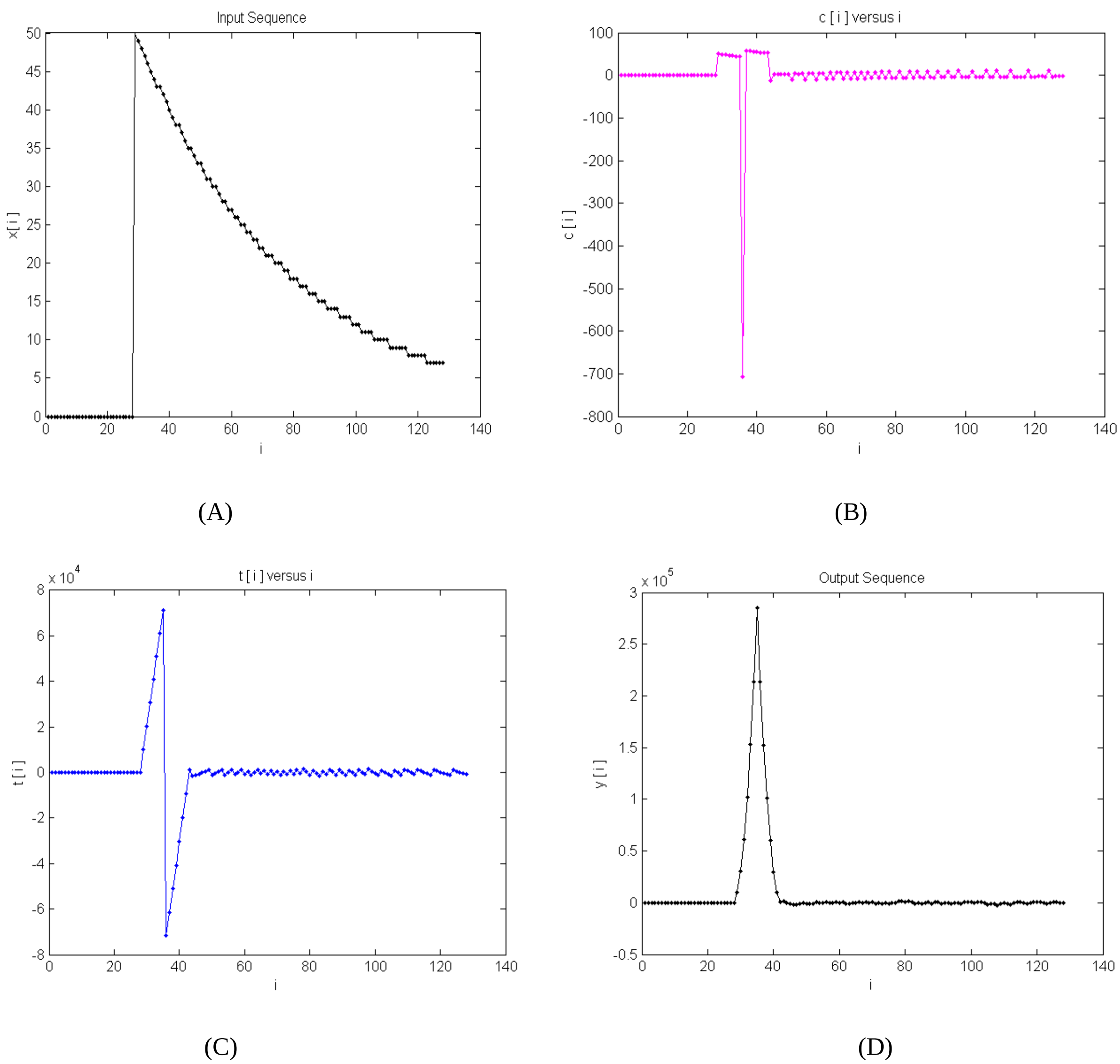

Figure 4: Cusp-like filtering simulation result for non piled up detector signal (A) input sequence-x[i], (B) sequence-c[i], (C) sequence-t[i] and (D) output sequence-y[i]

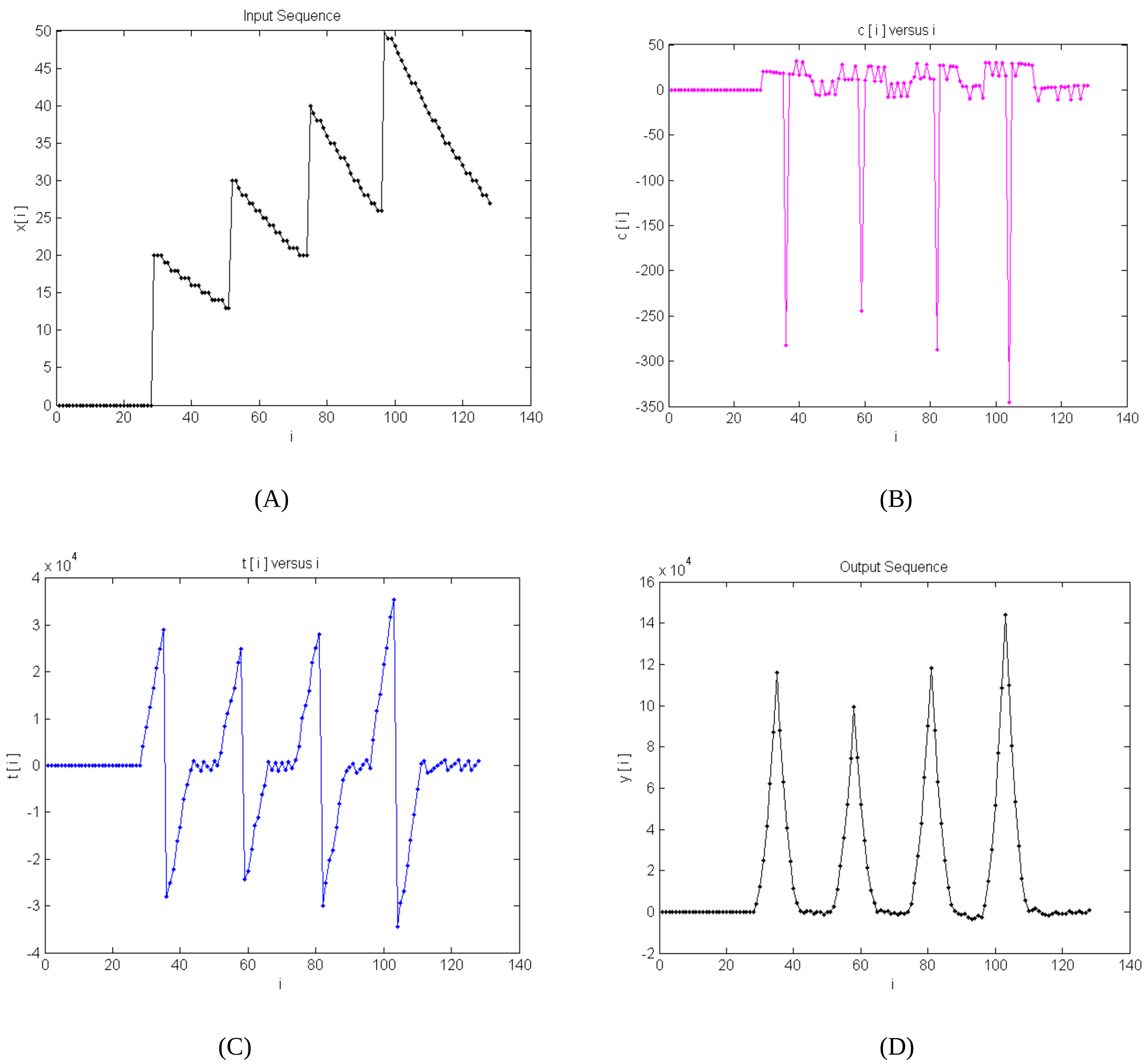

Figure 5: Cusp-like filtering simulation result for piled up detector signal (A) input sequence-x[i], (B) sequence-c[i], (C) sequence-t[i] and (D) output sequence-y[i]

IV. CONCLUSION

The VHDL simulation code for cusp-like filter was developed. The same was verified by observing the desired simulation results. It was also observed that the value of 'L' decides the rise/fall time. This parameter should be chosen carefully to minimize the pile up losses. The algorithm can be implemented into a digital hardware such as Field Programmable Gate Array (FPGA) to carry out the cusp-like filtering in real time applications.

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