Theoritical Considerations in the Design of Dead Time and Pileup Corrections in a Simple Two-Channel Digital Nuclear Radiation Measurement System

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Abstract

The sources of errors associated with the measurement of nuclear radiations includethe noise associated with the radiation pulse, the dead time required for the processing of the incident radiation pulse and the pileup of pulses. In analogue processing, these errors are often downplayed leading to appreciable errors in the observed results. Some digital processors have been designed and built aimed at solving these problems to a large extent but their complexities and high costs make them inaccessible for most laboratories especially in the developing countries. In this work, we have designed and implemented a cheaper digital nuclear radiation processing system that will significantly reduce these problems of errorsin nuclear spectroscopy. The processing scheme is based on digital pulse processing in both slow (energy) and fast (inspection) channels. The output of the fast channel is used for pileup inspection and slow channel peak capture while the slow channel provides for anaccurate pulse peak determination required for good energy resolution. The dead time effect is only restricted to the slow channel processing time which is the same as the pileup inspection time. The system functions in a non paralysable dead time effect manner with an appropriately derived dead time and pile-up error correction function.

Keywords: Digital Processing, Dead Time, Pileup, Error Correction

Introduction

Analogue and digital electronics means are used in the processing of nuclear radiations to determine the type, energy and intensity of such radiations. The processing is adversely affected by the responses of the electronic devices or components which culminate in 3 kinds of errors, namely, noise associated with the detected radiation and its processing, dead time and pileup losses.

In any system where noise is present and is capable of triggering the detection electronics or algorithm, it is not sufficient to simply count the triggering events and use assumptions about the distribution of arrival times to make pileup loss corrections in order to determine the incident rate of X- or gamma rays on the detector. It is necessary to understand the nature of the rejected events and their distribution [1]. The time interval which is required to process one pulse or event is called the dead time, implying that the system is dead to process another pulse or event during this time interval. It is assumed that each pulse occurring event is followed by a fixed deadtime interval t.

Thus, an important source of error comes from this finite time required by the counting electronics to detect and process radiation pulses. Dead time losses are usually compensated very well by the pulse-height analyzer, but pileup losses may not be [2]. The dead time is really due to the resolving time associated with the detector itself, its amplifier and the time required to convert the pulse to a digital form used for spectroscopy. During this dead time, the system cannot respond to other photons that hit the detector and these events will not be counted and thus are lost [3]. Depending on the behavior of a system, two kinds of dead-time can be distinguished: extended (or paralyzable) and nonextended (or nonparalyzable) dead time. In the case of an extended dead time, an event occurring during the time t belonging to a previous pulse, although it will be lost, still starts a new dead-time period. That is, it extends the dead time. In the case of a nonextended dead time, an event occurring during the dead time interval is lost and does not start a new dead period [4].

Dead time losses arise due to the time interval required to process a radiation pulse during which another detected radiation pulse cannot be processed. Pile-up loss arises due to the fact that two radiation pulses may arrive close to themselves in time with the result that their values overlap and are summed up such that the new summed value does not represent any of the two pulses. This constitutes serious distortions to the accuracy of measured pulse values.

Many modern popular gamma ray spectroscopy systems still use analogue schemes to implement the processing of radiation pulses through such circuits as differentiators and integrators (pulse shapers), voltage amplifiers, baseline restoration and pole zero cancellation circuits, while digital schemes are used to interface the analogue processor to the computer. It is obvious that with systems like this, the deadtime (pulse processing time) is a fixed single value; pileup inspection is effected through a combination of coincidence, anti-coincidence and discrimination circuits whose threshold values are arbitrarily and manually set. The effects of deadtime and pileup errors are often down-played, leading to serious errors in the observed results.

Digital processing systems do exist but many of the modern systems employ complex mathematical schemes such as adaptive trapezoidal/triangular filtering, symmetric or asymmetric cusp-like weighting and others. Such schemes require complex data operations such as digital multiplications, exponentiations, look-up tables for weighting functions, data set buffering for both time variant processing and inter-process synchronization and othersin addition to complex dead time and pile-up error correction functions[5,6,7,8]. These are expensive to implement in terms of the processing times and costs of the required electronic components. In order to reduce these losses without compromising on the efficiency of the spectrometry, we have designed a relatively cheap, simple and much more accurate computer controlled gamma ray spectroscopy system for laboratory uses especially in developing countries.

Description of the Digital Measurement System

Figure 1 shows the block diagram of the digital nuclear radiation measurement system which we have designed. In this figure, the circuit blocks in the dashed box 1 constitute the main processing system which includes the filter, peak detection and pile-up inspection (FPPI) circuits such as in the progenitor of the more complex and expensive commercial products [6,7].The dashed box 2 contains the Analogue Signal Conditioner (ASC) which includes the input amplifier stage and the Analogue-to-Digital Converter (ADC). Its role is to shape and convert the incoming radiation pulses to appropriate digital forms for further digital processing. The computer interface circuit (CIC) interfaces the main processing section to the computer. The operations of the ASC, CIC and the FPPI are controlled by the computer through the appropriate interface software.

The FPPI comprises a slow channel triangular shaping filter, a fast channel triangular shaping filter, a peak detector, a pileup inspector and an output buffer. The peak value of the slow channel output constitutes a measurement of the energy of the corresponding detected radiation. The function of the pileup inspector is to ensure that the slow channel pulse outputs are sampled only when the captured peak values result from a good pulse event.

A good pulse event is one which results from a pulse that is separated from both its predecessor and successor by a time interval that is at least greater than the slow channel's peaking time or pulse width. That is, a good pulse must be free of both leading edge and trailing edge pileups [9].

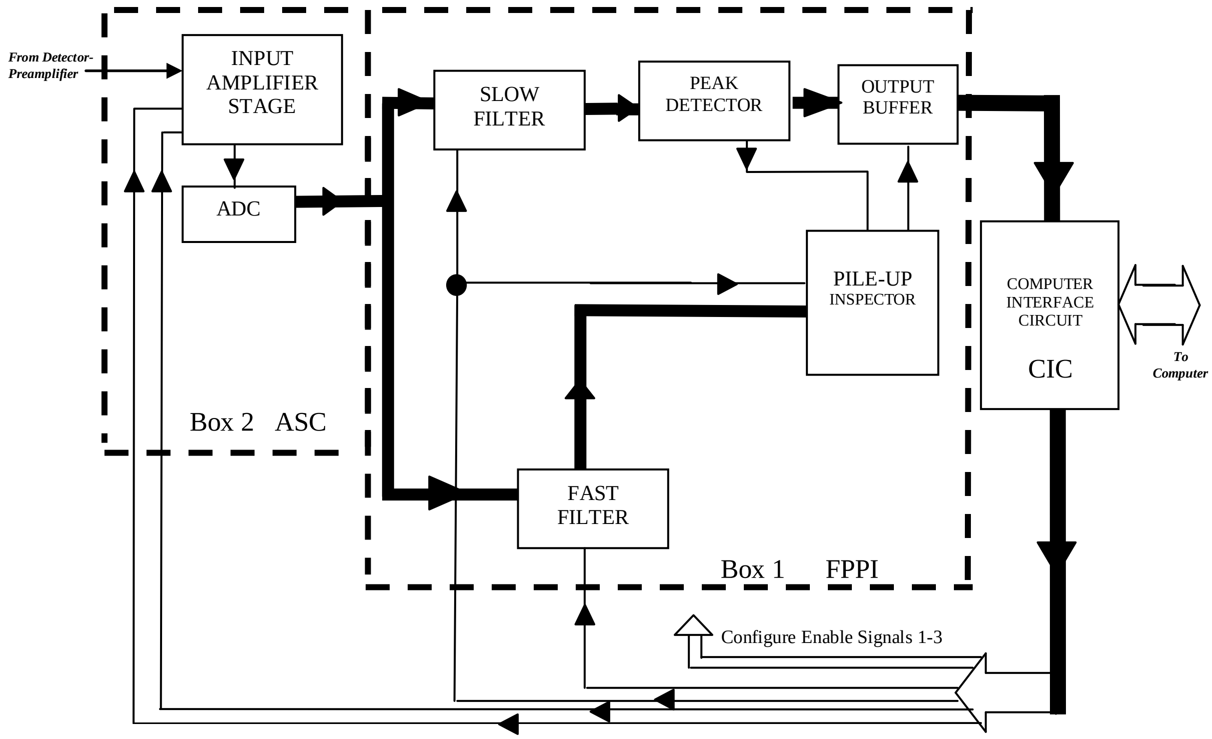

Figure 1: Diagram of the Measurement System with the Component Blocks.

The Deadtime and Pile-Up Correction Function

In nuclear radiation detection and measurement, the Poisson distribution is often an important and acceptable approximation of the distribution of counts. The Poisson distribution applies where the possible number of discrete occurrences is much larger than the average number of occurrences in a given interval of time. The number of possible occurrences is not known exactly in addition to the fact that the outcomes occur randomly and the probability of occurrence is not affected by previous occurrences. This is the case with nuclear radiation counts where the Poisson distribution is applied to obtain the popular general correction functions for both paralysable and non-paralysable dead time [4].These general correction functions are:

$$\eta = m/(1-m\tau) \text{ and } m = \eta e^{-\eta\tau} \qquad \text{----------1}$$

which for low rates ($\eta << 1/\tau$) become

$$m = \eta/(1+\eta\tau) \qquad \text{----------2}$$

for non-paralysable deadtime and

$$m = \eta e^{-\eta\tau} \qquad \text{----------3}$$

for paralysable deadtime

where η = true interaction rate, m = recorded count rate and τ = system deadtime. Non-paralysable deadtime model is preferred as it will be a lot easier to implement an appropriate circuit with accompanying effective corrective algorithm. In both cases of paralysable and non-paralysable deadtimes, it is desired that the term $\eta\tau$ tends towards zero, leading to the two count rates m and η being almost equal. Practically, this is not feasible; hence other techniques have to be devised.

Radiation is absorbed in a detector at a certain rate which is denoted as detector input count rate ICR_d [10]. The pulse processing circuit, due to pileup, detects a lower count rate than the detector. This processor detected count rate is denoted by ICR_p. It is to be noted that this phenomenon is a general characteristic of all analogue and digital detection circuits.

Thus, for a processor channel that suffers from non-paralysable deadtime effect as in the case of the implemented digital system, the maximum count rate from the processor channel depends on pulse-pair resolution which is the minimum interval at which each pulse can be separated. In other words, it is the system's deadtime. The reciprocal of this deadtime provides the maximum count rate. However, since the pulse events occur randomly, there is the probability of pulse event pileup. With this probability of pileup, the actual maximum count rate would be far lower than the reciprocal of the deadtime. With the processor detected count rate. ICR_p, the measured count rate denoted as OCR, the system's deadtime denoted as τ, the loss of count rate due to the probability of pile-up (ICR_p – OCR) is

$$ICR_p - OCR = ICR_p * OCR * \tau \qquad \text{----------4}$$

then the processor detected count rate ICR_p becomes

$$ICR_p = OCR/(1 - OCR * \tau) \quad \text{or}$$
$$OCR = ICR_p/(1 + ICR_p * \tau) \qquad \text{---------5}$$

which is the correction function for non-paralysable deadtime as shown in eqn(5). This equation corrects the count error and offers excellent linearity over a wide counting range.If eqn(5) is applied to the concept of slow and fast pulse shaping schemes that suffer from non-paralysable deadtime effect as in Figure 1, the associated parameters can be defined as follows:

ICR_p is a fraction of ICR_d that is measured from the fast channel and depends on the fast channel's peaking time τ_f. The shorter τ_f is, the higher is the value of ICR_p. In addition, OCR_s is a fraction of ICR_pwhich is measured from the slow channel. It is dependent on the slow channel's peaking time τ_s. The shorter τ_s is, the higher is the value of OCR_s.

From basic definitions,

$$\text{Input Count Rate } (ICR_p) = \frac{\text{Total counts (including pile-ups)}}{\text{Total time of all recordings}} \qquad \text{--------6}$$

$$\text{Output Count Rate } (OCR_s) = \frac{\text{Recorded Counts}}{\text{Realtime of Recorded Counts}} \qquad \text{--------7}$$

The ratio of the two channels' peaking times is:

$$\text{Ratio } (\eta) = \frac{\text{Slow filter peaking time } (\tau_s)}{\text{Fast filter peaking time } (\tau_f)} \quad \text{· ----8} \quad \frac{\tau_s}{\tau_f}$$

Applying eqn(5) to both the slow and fast channels respectively leads to:

$$OCR_s = \frac{ICR_p}{1 + (ICR_p * \tau_s)} \qquad \text{---------9}$$

$$OCR_f \approx ICR_p = \frac{ICR_d}{1 + (ICR_d * \tau_f)} \qquad \text{--------10}$$

where the subscripts *s* and *f* refer to the slow and fast channels. (The output of the fast channel filter is approximately equal to its input since there is virtually no loss of count rate, ie $OCR_f \approx ICR_p$). It is easily seen that there is a link between eqns (9) and (10) when the ratio η is taken into consideration. Hence, from eqn(8),

$$\tau_s = \eta\tau_f \qquad \text{--------11}$$

Substituting eqn(11) into eqn(9) gives

$$OCR_s = \frac{ICR_p}{1 + (ICR_p * \eta * \tau_f)} \qquad \text{--------12}$$

from which, $ICR_p = \dfrac{OCR_s}{1-(OCR_s * \eta * \tau_f)}$ --------13

Making ICR_d the subject from eqn(10) gives

$$ICR_d = \frac{ICR_p}{1-(ICR_p * \tau_f)} \quad \text{-------14}$$

Substituting eqn(13) into eqn(14) gives

$$ICR_d = \frac{OCR_s /(1-OCR_s * \eta\tau_f)}{1-(\dfrac{OCR_s}{1-OCR_s * \eta\tau_f} * \tau_f)} \quad \text{--------15}$$

Or

$$ICR_d = \frac{OCR_s}{1-OCR_s * \tau_f(\eta+1)} \quad \text{--------16}$$

Equation(16) gives the detector corrected count rate at low to very high counts.

Observations

It is to be noted that OCR_s is the ratio of the total counts without pileup from the slow channel N_s to the total time T_s for which the total count was collected ie

$$OCR_s = N_s/T_s \quad \text{-------17}$$

It is also to be observed that the slow channel peaking time τ_s determines the maximum OCR as the higher it is, the lower is the max OCR since $OCR_{max} = 1/\tau_s$ whileη plays a major role in the correction function in that as it increases, the correction becomes better. However, as η increases, the fast channel peaking time becomes shorter thereby increasing the noise content of the channel. It is further noted that the slow channel peaking time τ_s determines the maximum output count rate OCR as the higher it is, the lower is the max OCR since $OCR_{max} = 1/\tau_s$. We present in Tables 1 and 2 the theoretical detector input count rate (ICR_d) as a function of the output count rate (OCR_s) for various values of T_s, T_f, η and OCR_{smax}.From Tables 1 and 2, it is observed that at short filtering time τ_s, the correction is significant even at low count rates (above 1%). There is a limit to the value of η which causes the denominator of the correction function to have a negative value, showing that OCR_{max} has been exceeded.

OCR_s	$OCR_s * \tau_f(\eta+1)$	$1-[OCR_s * \tau_f(\eta+1)]$	$ICR_d = OCR_s/$ $1-[OCR_s * \tau_f(\eta+1)]$	Corrected Error in %
1,000	17.6×10^{-3}	0.9824	1,018	1.8
2,000	35.2×10^{-3}	0.9648	2,073	3.65
3,000	52.8×10^{-3}	0.9472	3,167	5.57
5,000	88.0×10^{-3}	0.912	5,482	9.64
10,000	176×10^{-3}	0.824	12,136	21.36
15,000	264×10^{-3}	0.736	20,380	35.87
20,000	352×10^{-3}	0.648	30,864	54.32
30,000	528×10^{-3}	0.472	63,559	111.86
50,000	880×10^{-3}	0.12	416,667	733.33
80,000	1408×10^{-3}	Negative value		

Table 1: Theoritical Detector Input Count Rate ICR_d for various Output Count Rate (OCR_s) of the Slow Filter Channel Using $\tau_s = 16\ \mu S$, $\tau_f = 3.2\ \mu S$ and $\eta = 5$, $OCRs_{max} = 62{,}500$

OCR_s	$OCR_s * \tau_f(\eta+1)$	$1-[OCR_s * \tau_f(\eta+1)]$	$ICR_d = OCR_s / 1-[OCR_s * \tau_f(\eta+1)]$	Corrected Error in %
1,000	19.2×10^{-3}	0.9808	1,020	2.0
2,000	38.4×10^{-3}	0.9616	2,080	4.0
3,000	57.6×10^{-3}	0.9424	3,183	6.1
5,000	96.0×10^{-3}	0.904	5,531	10.62
10,000	192×10^{-3}	0.808	12,376	23.67
15,000	288×10^{-3}	0.712	21,067	40.45
20,000	384×10^{-3}	0.616	32,468	62.34
30,000	576×10^{-3}	0.424	70,755	135.85
50,000	960×10^{-3}	0.04	1,250,000	2400
80,000	1536×10^{-3}	Negative value		

Table 2: Theoritical Detector Input Count Rate ICR_d for various Output Count Rate (OCR_s) of the Slow Filter Channel Using τ_s = 16 µS, τ_f = 1.6 µS and η = 10, $OCRs_{max}$ = 62,500

When a detector-preamplifier or an analogue shaping amplifier is used instead of digital filters, then there is no fast peaking time and eqn(16) becomes

$$ICR_d = \frac{OCR_s}{1-OCR_s*(\tau_s+\tau_f)} = \frac{OCR_s}{1-OCR_s*\tau_s} \quad \text{--------------18}$$

where τ_f is now zero. Equation 15 is the popular correction function. In Tables 3 and 4 we present the theoretical corrections for ORTEC575A shaping amplifier and ORTEC 276 detector-preamplifier respectively. From these tables, one observes that the corrections are significant at all count rates. These corrections are not implemented at present in most popular spectroscopy systems.

OCR_s	$OCR_s * \tau_f(\eta+1)$	$1-[OCR_s * \tau_f(\eta+1)]$	$ICR_d = OCR_s / 1-[OCR_s * \tau_f(\eta+1)]$	Corrected Error in %
1,000	26.4×10^{-3}	0.9736	1,027	2.7
2,000	52.8×10^{-3}	0.9472	2,112	5.6
3,000	79.2×10^{-3}	0.9208	3,258	8.6
5,000	132.0×10^{-3}	0.868	5,760	15.2
10,000	264×10^{-3}	0.736	13,587	35.87
15,000	396×10^{-3}	0.604	24,834	65.56
20,000	528×10^{-3}	0.472	42,373	111.87
30,000	792×10^{-3}	0.208	144,231	380.77
50,000	1320×10^{-3}	Negative value		

Table 3: Theoritical Correction for ORTEC 575A Shaping Amplifier with a 3 µS Shaping Time Constant ie 26.4 µS Pulse Width at 0.1 %, $OCRs_{max}$ = 37,879

OCR_s	$OCR_s * \tau_f(\eta+1)$	$1-[OCR_s * \tau_f(\eta+1)]$	$ICR_d = OCR_s / 1-[OCR_s * \tau_f(\eta+1)]$	Corrected Error in %
1,000	50×10^{-3}	0.95	1,053	5.3
2,000	100×10^{-3}	0.9	2,222	11.1
3,000	150×10^{-3}	0.85	3,529	17.63
5,000	250×10^{-3}	0.75	6,667	33.34
10,000	500×10^{-3}	0.5	20,000	100
15,000	750×10^{-3}	0.25	60,000	400
20,000	1000×10^{-3}	0		
30,000	1500×10^{-3}	Negative value		

Table 4: Theoritical Correction for ORTEC 276 Detector-Preamplifier with a Pulse Width of 50 µS, $OCRs_{max}$ = 20,000

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