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Performance of Higher Order Campbell methods, Part I: review and numerical convergence study

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ABSTRACT

This paper investigates, through numerical simulations, the performance of a signal analysis method by which a high temperature fission chamber can be used over a wide range of count rates. Results reported in a previous paper (Elter et al., 2015 [1]) indicated that the traditional Campbell method and the pulse mode cannot provide a sufficient overlap at medium count rates. Hence the use of the so-called Higher Order Campbell (HOC) methods is proposed and their performance is investigated.

It is shown that the HOC methods can guarantee the linearity (i.e. correctness) of the neutron flux estimation over a wide count rate, even during transient conditions. The capabilities of these methods for suppressing parasitic noise (originating from various sources) are verified.

1. Introduction

Sodium-cooled fast reactors (SFRs) are among the advanced reactors selected by the Generation IV International Forum. In Europe, the development of an innovative pool-type SFR is under way, led by the French CEA and its industrial partners [2]. The development also concerns the neutron flux monitoring system, which is the subject of this paper.

As described in several publications in the literature [3–5], fission chambers capable of operating at high temperatures (high temperature fission chambers, HTFC) are the most promising candidates for neutron flux monitoring in SFRs. HTFCs have long been used for neutron flux monitoring [6,5]. However, a few aspects of their operation and use have not been solved satisfactorily. This paper attempts to solve some of these shortcomings.

One such point is that fission chambers operate in different modes, with corresponding different electronics and signal processing algorithms, at low (start-up) and high (full power) detection rates, respectively [7]. At low detection rates, when the signal has the shape of individual "spikes", a pulse counting technique, based on level crossing is applied. At higher count rates, when the detector pulses overlap, pulse counting becomes impossible and the detection rate is estimated from the detector current with the so-called Campbelling techniques. In its traditional form this means that the mean count rate is determined from the variance of the detector current. This method has the advantage that it suppresses the (unwanted) contribution from minority components, such as counts from gamma photons.

In order to have a correct estimate of the neutron flux for all count rates, there should be a sufficiently wide overlap between the two operating regimes of the detector, where both methods supply correct results. Under ideal circumstances, the traditional Campbell method would provide a sufficient overlapping since, in principle, the Campbell formula is valid also for individual pulses. However, as the simulation studies of our previous work showed [1], at low count rates that the traditional Campbell method is vulnerable to the effect of parasitic noise (detection and electronic noise), and hence the overlap is not guaranteed.

To remedy this problem, the generalisation of the Campbelling technique was proposed through the application of the so-called Higher Order Campbelling (HOC) methods [8–10]. These use the higher order moments (cumulants) of the detector current to estimate the detection rate. Although the theoretical relationship between the higher order cumulants and the mean detection rate has long been known, the applicability and performance of these methods in practical applications has not been tested. The applicability concerns essentially two aspects. One is the sensitivity of the accuracy to parasitic (inherent) noise in the detection process and the electronics, which deteriorates the performance of all order Campbelling methods at low count rates. The other aspect is that the theoretical advantages of the use of higher order cumulants [11–13] are offset by the fact that in reality one only

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uses an estimate of the theoretical cumulants, and the error of the estimate increases with the order of the moment to be estimated.

This paper addresses the question of linearity of HOC methods and the practical applicability of the cumulant estimators with the use of an advanced simulation package. In previous work, in order to investigate the question of the linearity of the pulse and the traditional Campbelling modes, a dedicated code was developed for the simulation of fission chamber pulse trains [1]. Recently the code was updated to be capable of simulating detector signals with time dependent count rate to study transient scenarios. The upgraded code was used in the recent study. The code can handle arbitrary signal shapes, charge distributions and the presence of added noise. With the help of the code, a quantitative analysis of the HOC methods was made.

As the continuation of this paper, a second part, describing the related experimental results, is planned to be published. Part II will introduce the calibration methodology to unfold the count rate and the reactor power information from the cumulants of the signal [22].

In this paper the principles of the HOC methods, their applications, and the results related to their performance study are described. First, the filtered Poisson process that permits us to describe a conditioned signal of a fission chamber and our developed simulation code is discussed briefly. Second, a brief overview of higher order methods, and the estimation of higher order cumulants is given. Finally, the performance of the higher order Campbelling modes is investigated for several cases, such as electronic noise, gamma background radiation and transient events. The investigations verify the expected advantages of HOC methods and explore the possible drawbacks of orders higher than 3 via computational simulations.

2. Physical processes in fission chambers

Fission chambers are nuclear detectors that are widely used for online neutron flux measurements. This type of detector is an ionisation chamber, containing fissile material in order to detect neutrons. The most common design consists of one or more electrode pairs, of which at least one electrode is coated with a fissile layer, ranging from a few micrograms to a few grams. The spacing between each anode and cathode goes from tens of microns to a few millimeters. The chamber itself is filled with an argon-based gas pressurised at a few bars. The processes leading to a current pulse after a neutron entering the chamber are the following:

(a) When a neutron reaches the fissile coating, it is likely to induce a fission event which generates (usually) two heavily charged ions, the fission products, emitted in two nearly opposite directions.
(b) The heavy ion which is emitted out of the fissile layer ionises the filling gas along its trajectory (therefore creates electron/ion pairs).
(c) A DC-voltage of a few hundred volts is applied between the electrodes, therefore the electrons and positive gas ions drift across the filling gas in opposite direction towards the anode and the cathode respectively
(d) During the drift both the electrons and the gas ions induce a current pulse (named in this document as electronic and ionic pulse) in the electrodes.

3. Simulation of the fission chamber signals

Since the basic principles and assumptions on the character of the fission chamber signals were already described in [1,10], only a brief description will be given here. The fission chamber signal is described as a Poisson pulse train, or shot noise, also called a filtered Poisson process [14]. In such a stochastic process the time interval between each pair of consecutive events has an exponential distribution with an intensity parameter s_0 [15]. The intensity, or count rate, is proportional to the neutron flux level around the detector. In this section the signal is considered as the one induced by the electronic pulses (therefore the signal contains only one type of pulse), but later the impact of ionic pulses is also investigated. The form of an individual pulse is assumed to be

$$q \cdot f(t) \tag{1}$$

where $f(t)$ is the (deterministic) normalised pulse shape (the response function of the detector) and q is a random variable representing the pulse charge, characterised with a charge distribution $w(q)$.

The detector signal $\eta(t)$ is a superposition of pulses of the form

$$\eta(t) = \sum_{k=0}^{N(t)} q_k \cdot f(t - t_k) \tag{2}$$

where t_k are the exponentially distributed neutron arrival times at the detector, q_k are the random pulse charges, and $N(t)$ is the number of pulses having arrived until time t ($N(t)$ is a Poisson distributed random variable). The integral of the shape function $f(t)$ in (2) is normalised to unity. The simplest approximation is if the pulse charges are considered as deterministic (constant). This is the case which will be considered in the quantitative work in this paper too, since the simulation studies of our previous work [1] showed that the random character of the pulse charges did not have any influence on the detector signal characteristics that were studied.

The new features of the current simulation model, compared to that used in Ref. [1] are as follows. The first concerns the signal pulse shape $f(t)$. In the previous work [1], similar to the theoretical considerations [10], the pulse had a form of a step jump at $t=0$, followed by a monotonically decreasing (exponential) or non-increasing (rectangular/boxcar shape) behaviour, characterised by one single parameter. In the present work, the pulse shape was chosen to have the form of a damped exponential:

$$f(t) = \frac{e^{-t/p_1} - e^{-t/p_2}}{\int_0^\infty (e^{-t/p_1} - e^{-t/p_2})\, dt}. \tag{3}$$

This form is more realistic, i.e. it avoids the discontinuity (jump) of the pulse at $t=0$, rather it is non-monotonic and it consists of a fast rising and a slowly decaying part. Hence it also allows a more varied pulse shape, due to the two different parameters p_1 and p_2. With the signal shape given by Eq. (3), the ionic and electronic components of the pulse can be modelled by suitable choice of the pulse parameters, i.e. the time constants p_1 and p_2 of the pulse shape $f(t)$ and the pulse charge $\langle q \rangle$.

For the quantitative work, reference pulse parameters were chosen to describe both the electronic and the ionic pulses. The characteristics of the pulses are summarised in Table 1, and Fig. 1 shows a graphical representation of the electronic pulse. The parameters have realistic orders of magnitudes and are based on

Table 1
The reference pulse.

Type	e^-	Ion
Time parameter p_1	20 ns	2 μs
Time parameter p_2	4 ns	0.4 μs
Mean charge $\langle q \rangle$	0.1 pC	0.1 pC
Amplitude a	3.34 μA	34 nA
Pulse width	100 ns	10 μs
Resolution	1 ns	1 ns