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Performance of Higher Order Campbell methods, Part II: calibration and experimental application

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ABSTRACT

Applying Higher Order Campbelling methods in neutron flux monitoring with fission chambers is advantageous due to their capabilities to suppress the impact of unwanted noises and signal contributions (such as gamma radiation). This work aims to verify through experimental results that the basic assumptions behind the Higher Order Campelling methods are valid in critical reactors.

The experiments, reported in this work, were performed at the MINERVE reactor in Cadarache. It is shown that the calibration of a fission chamber and the associated electronic system is possible in higher order mode. With the use of unbiased cumulant estimators and with digital processing, it is shown that over a wide count rate range, accurate count rate estimation can be achieved based on signal samples of a few *ms*, which is a significant progress compared to similar experimental results in the literature. The difference between the count rate estimated by pulse counting and by the Higher Order Campelling is less than 4%.

The work also investigates the possibility of monitoring transient events. For this purpose, a control rod drop event was followed in Higher Order Campbelling mode.

1. Introduction

Sodium-cooled fast reactors (SFRs) are among the advanced reactors selected by the Generation IV International Forum [1]. 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.

Fission chambers are the most promising candidates for neutron monitoring in SFRs. Such detectors traditionally operate in three modes: pulse mode at low flux levels, Campbelling or fluctuation mode at medium flux levels, and current mode at high flux levels. Recently it was shown that to guarantee the overlap of the pulse and Campbelling mode, one needs to design dedicated fission chambers [3]. A design independent alternative can be the operation of the fission chambers in Higher Order Campbell (HOC) mode [4,5]. As detailed in Part I of this work [6], the application of higher order methods is limited by the fact that the error of the estimation increases with the order of the method, therefore larger signal samples are needed. The rapid development of digital measurement devices (such as FPGAs, field programmable gate arrays) brings recent attention to these methods, since the reliable estimation of the higher order moments of the signal became achievable.

In Part I of this work, the performance of the higher order methods was extensively investigated through numerical simulations [6]. In the same work, it was shown that higher order methods are capable to suppress the disadvantageous impact of various noises and unwanted signal contributions. It was found that the application of the third order method is reliable, and that it is redundant to apply higher than third orders.

As a continuation of that work, this paper investigates experimentally the application of the third order Campbelling method. A simple approach is proposed to make use of the third order cumulants of the signal in the time-domain, instead of dealing with the third order spectra of the signal as [7]. With the use of unbiased cumulant estimators and with digital processing, it is shown that accurate count rate estimation can be achieved based on signal samples of a few *ms*, which is a significant progress compared to similar experimental results in the literature [8]. This paper presents the methodology of the calibration to link the cumulants of the signal to the power of the reactor and to the fission rate of the chamber. The disadvantages of the calibration are discussed. A rather involved calibration methodology based on the spectral properties of the signal can be found in [9] for the traditional Campbelling mode.

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The current work is a step towards the implementation of an FPGA-based Campbelling measurement system, which is capable of real-time flux monitoring.

First, the Higher Order Campbell theorem is briefly discussed. Second, Section 3 presents the experimental setup, the noise of the system and addresses the general applicability of Campbell's theorem in critical reactors. Section 4 summarizes the measurement results during stationary and transient reactor states, and the methodology to calibrate fission chambers in higher order mode. The accuracy of the calibration is assessed with the help of pulse counting techniques, and an empirical calibration, based on the pulse counted results, is proposed.

2. Higher Order Campbell method

In Part I [6], the general form of the Campbell relationships [10,11] for a homogeneous (i.e. having a constant count rate) shot noise signal $y(t)$ consisting of general pulses $f(t)$ with a charge distribution, and count rate s_0 (such signal is an appropriate approximation of the fission chamber signals [3]), was given. Similarly, the general Campbell equations can be given by introducing the pulse amplitude distribution instead of the charge distribution as [12]

$$\kappa_n(y(t)) = s_0\langle a^n\rangle \int_{-\infty}^{+\infty} f(t)^n dt = s_0 \cdot C_{a,n} \quad (1)$$

where $\kappa_n(y(t))$ is the nth order cumulant of the distribution of the signal $y(t)$ and $\langle a^n\rangle$ stands for the nth raw moment of the pulse distribution. Commonly, the methods in which $n \geq 3$ are called higher order methods. The pulse function $f(t)$ is normalized to the amplitude.

Eq. (1) shows that if the pulse shape $f(t)$ and the charge or amplitude distribution are known (therefore the calibration coefficient $C_{a,n}$ – later referred to only as C_n – is determined), and the cumulant (of any order) of the signal is measured, then the mean count rate s_0 of the signal can be estimated. Eq. (1) assumes that the signal contains pulses with the same shape. It is shown later, that this assumption is not valid in multi-coating chambers. Section 4.2 addresses the bias of considering the pulse shape as constant. For this investigation the pulse shape will be considered as bimodal.

The coefficient C_n links the signal statistics to the fission rate directly, which means that such a calibration is independent of the neutron environment or neutron spectra. The present work aims to estimate the calibration coefficient by investigating the mean shape and the amplitude distribution of the pulses (see Section 4.3), and also by performing an empirical calibration through estimating the count rate with pulse counting technique.

It was shown previously in [6] that the application of higher order methods sufficiently suppresses the impact of various noises: the parasitic noise of the system, the unwanted signal contributions of ionization processes not originating from the fission events, and the ionic contribution of the charge creation in the filling gas.

In this work the cumulants are estimated during the post-processing of the measured and recorded signals. The unbiased cumulant estimators, or k-statistics, are applied [14], for which the calculation of the nth order sums of the signal values are needed. This allows a simple estimation in the time-domain with a relatively fast convergence. Practically, estimating the cumulant means, that a finite and discrete-time signal slice is recorded, and the cumulants of the distribution of these sampled values are computed. Fig. 1 shows an example of the recorded signal (the details of the system for recording are given in the next section), its probability density function and the related cumulant estimations.

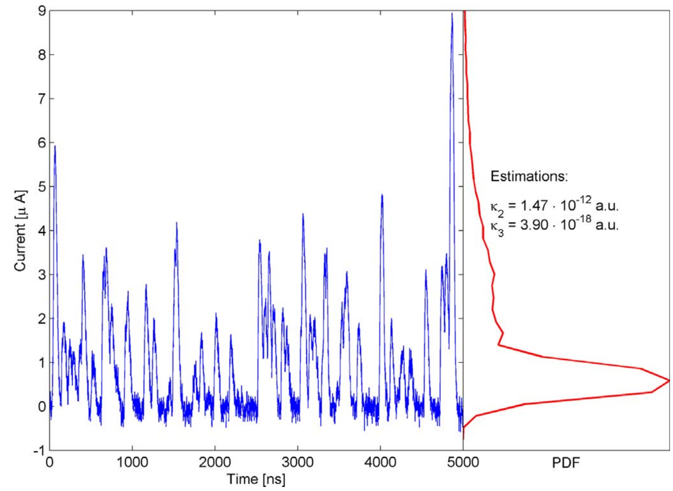

Fig. 1. An example of a recorded signal slice and its distribution at 20 W.

3. Experimental setup

The experimental setup consisted of a current-sensitive fission chamber placed in the reflector zone of the MINERVE reactor. MINERVE is a pool type zero-power, light water reactor, operated at CEA Cadarache with a maximum power of 80 W.

In the experiment a CFUL01 fission chamber (manufactured by Photonis) was studied. The CFUL01 is a multi-electrode and multi-coating detector, which means that the chamber contains three coaxial electrodes and four fissile coatings of enriched uranium, as illustrated in the schematic radial cross section of the chamber, Fig. 2. The sensitive length of the detector is 211 mm, the outer radius of the first anode is 14 mm, the inner and outer radii of the cathode are 16 and 17 mm, and the inner radius of the second anode is 19 mm. Therefore the gas gap is 2 mm wide for both the inner and outer chambers. The nominal operating voltage is 600 V (and the maximum voltage is 800 V at 20 °C, while the limit is 1300 V with no radiation). The filling gas is argon with 4% nitrogen at 250 kPa (at room temperature). The fissile deposit consists of U_3O_8, with the U235 content enriched to 90%, with a surface density of 1.32 mg/cm^2. The thickness of the deposit is around 1.5 μm (in Fig. 2 the thickness of the circles referring to the deposit was enlarged only for the illustration purpose). The advantage of using detectors with multiple coatings is to increase the fissile

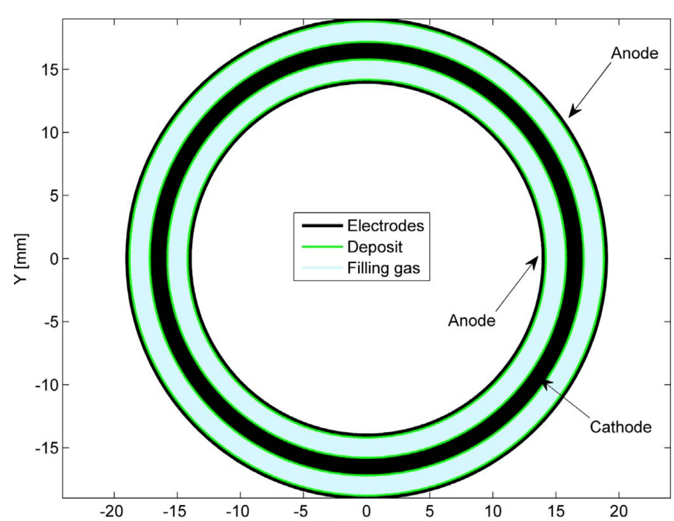

Fig. 2. Illustration of the radial cross section of the CFUL01 chamber.