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Sensitivity of power spectral density techniques to numerical parameters in analyzing neutron noise experiments

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A B S T R A C T

Power spectral density (PSD) methods are well-known and widely used for the analysis of neutron noise experiments and obtaining the reactor's integral kinetic parameters, i.e., the effective delayed neutron fraction β_{eff} and the prompt neutron generation time Λ. Many uncertainties are usually associated with PSD methods, e.g., statistical fluctuations in the neutron flux, power drifts, uncertainties in the Diven factor, the integral fission rate, and in the reactivity value. However, the uncertainty associated with the numerical parameters used in the power spectrum calculation procedure is hardly discussed in the literature and generally overlooked.

The aim of this paper is to study the uncertainties in the kinetic parameters of a reactor core, obtained by PSD methods, which are associated with the numerical parameters of the method. A comprehensive estimation of the kinetic parameters, including all other uncertainties, is not pursued. In this paper, PSD methods are implemented to analyze critical and subcritical configurations of the MINERVE zero power reactor in order to measure its integral kinetic parameters β_{eff} and Λ. Both cross and auto power spectral densities are calculated and the kinetic parameters are obtained via Lorentzian curve fitting over the calculated PSD. The sensitivity of the obtained kinetic parameters to the choice of numerical parameters used for spectrum calculations is studied and found to be significant with respect to other uncertainties. A novel methodology is proposed for analyzing the kinetic parameters' sensitivity to the PSD calculations and for quantifying the associated uncertainties.

1. Introduction

A set of neutron noise measurements has been performed on the MINERVE zero power reactor at Cadarache research center in France during September 2014. This experimental campaign was conducted in the framework of a tri-partite collaboration between CEA, PSI and SCK-CEN (Geslot et al., 2015; Perret, 2015; Gilad et al., 2016). Measurements were then also processed and analyzed in the framework of a collaboration between CEA, Ben-Gurion University of the Negev (BGU), and the Israeli Atomic Energy Commission (IAEC). The main purpose of the campaign was to obtain the core kinetic parameters using various existing and novel noise techniques and compare it with recent measurements. The last time a similar campaign was performed in MINERVE was in 1975 and the core configuration was different (Carre and Oliveira, 1975). This campaign is a continuation of a previous one aimed at determining the delayed neutron fraction β_{eff} in the MINERVE reactor using in-pile oscillations technique (Gilad et al., 2015).

Several well-known and widely used neutron noise techniques were implemented for analyzing the experimental measurements, e.g., power spectral density (PSD, also known as Cohn-α method), Feynman-Y, and Rossi-α methods (Geslot et al., 2015; Perret, 2015). These methods were used to obtain the reactor core's integral kinetic parameters, i.e., the effective delayed neutron fraction β_{eff} and the prompt neutron generation time, including a thorough analysis of the associated uncertainties. More specifically, PSD methods are considered as the standard data processing procedure in the case of a current acquisition system that works at high fission rates by digitizing the current signal issued by fission chambers (Diniz and dos Santos, 2002; dos Santos et al., 2006; Geslot et al., 2015). Such a system has recently been developed and qualified by CEA and is able to process signals on line without any data loss (de Izarra et al.,

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The statistical uncertainties associated with the PSD method are usually thoroughly analyzed and are propagated to the final results, i.e., the integral kinetic parameters, using well established methodologies and considerations. For example, both Geslot et al. (2015) and Perret (2015) recommend using the values obtained by the cross power spectral density (CPSD) estimator following data processing considerations and final uncertainties associated with the results. In their studies, this estimator has proved to be very robust and produced minimum uncertainties. The uncertainties usually considered in the PSD method include statistical fluctuations in the neutron flux, power drifts, uncertainties in the Diven factor, in the integral fission rate, and in the reactivity value. For example, the high-level analysis by Geslot et al. (2015) using PSD techniques leads to uncertainties of 1.8–2.8 pcm in the value of β_{eff} and 0.7–1.3 μs in Λ (at 1σ).

On the other hand, the uncertainty associated with the numerical parameters used in the power spectrum calculation procedure, e.g., the time bin size and the number of points taken in each Fourier transform (buffer size), is hardly discussed in the literature and generally overlooked. Despite their conspicuous importance (as demonstrated in this paper), very little considerations are usually given to their values. These values are often determined rather arbitrarily according to the acquisition system technical specifications and the bias degree of the residuals in the curve fitting procedure. Moreover, well-defined criteria or methodologies for setting and tuning these numerical parameters, as well as for evaluating their associated uncertainties, are generally absent. Examples of numerical parameters used for power spectrum calculations in different studies are given in Table 1.

It should be noted that the precise values of the kinetic parameters are of less importance in this study. Instead, the important result is the methodology for estimation of the propagated uncertainties associated with the numerical parameters and the fact that these are of significant magnitude compared to other uncertainties, thus should not be ignored.

In this paper, the sensitivity of the PSD method to numerical parameters used in the power spectrum calculation is studied by analyzing noise measurements performed in the MINERVE reactor core at three different reactivity states. The associated numerical uncertainties are evaluated and a methodology for optimal determination of these parameters is proposed. The experimental setup is described in section 2, the PSD formalism is introduced in section 3, and the CPSD results for the critical state Acq12 are described and discussed in sections 4. The CPSD results for the subcritical states Acq16 and Acq19 are described in sections 4.3. APSD results for the different reactivity states are described section 4.4 and the conclusions are discussed in section 5.

Table 1
Example of numerical parameters used for power spectrum calculations in different studies.

Reference	Number of points in each Fourier transform	Time bin size [ms]
Kitamura et al. (1999)	–	0.512
Diniz and dos Santos (2002)	800	0.03–2
Diniz and dos Santos (2006)	1600	160
	800	10
dos Santos et al. (2006)	400–800	–
dos Santos et al. (2013)	8192	0.2
Geslot et al. (2015)	2000	1
Perret (2015)	2048	1

2. Experimental setup

The MINERVE reactor is a pool-type ($\sim$120 m^3) reactor operating at a maximum power of 100 W with a corresponding thermal flux of 10^9 n/cm$^2\cdot$s (Bignan et al., 2010). The core is composed of a driver zone, which includes 40 standard highly enriched MTR-type metallic uranium alloy plate assemblies surrounded by a graphite reflector. An experimental cavity, in which various UO_2 or MOX cladded fuel pins can be loaded in different lattices, reproducing various neutron spectra (Bignan et al., 2010; Hudelot et al., 2004), is located in the center of the driver zone. During the experimental campaign, the central experimental zone was loaded with 770 3% enriched UO_2 fuel rods arranged in a lattice representative of a PWR spectrum. An oscillator piston, capable of moving periodically and vertically between two positions located inside and outside of the core is located inside the experimental zone. A general view of the MINERVE reactor is shown in Fig. 1, together with schematic drawings of the reactor geometrical configuration and the MAESTRO core configuration (Leconte et al., 2013).

During the measurement campaign, neutron noise experiments have been conducted in three reactor states; one very close to critical state (marked as "Acq12") and two different subcritical states (marked as "Acq16" and "Acq19"). The different criticality states were obtained by inserting one of the four control rods into the core. The reactor configuration was that of the MAESTRO program (Leconte et al., 2013), representing a PWR spectrum in the central experimental cavity, as shown in Fig. 1. Two large fission chambers with approximately 1 g of ^{235}U have been installed next to the driver zone (denoted n° 670 and n° 671 in Fig. 1). In order to minimize flux disturbances in the detectors during measurement, reactor criticality was controlled by control rod B1, which is far from the two detectors. During the measurements, the power was regulated by an automatic piloting system that makes use of a low efficiency rotating control rod with cadmium sectors.

The signals were acquired using fast amplifiers and CEA-developed multipurpose acquisition system X-MODE (Geslot et al., 2005). The signals were acquired in time-stamping mode with a resolution of 25 ns. It should be noted that the processed signal was not the digitized, continuous current of a detector. Instead, the number of pulse detections is summed up in time bins to generate a discrete count rate, which is assumed to be proportional to the momentary (sampled) value of the neutron flux.

The only slightly subcritical measurement Acq12 has been conducted at a power of 0.2 W with detectors' count rate around 5.5×10^5 cps. The subcritical measurements Acq16 and Acq19 have been conducted with detectors' count rate around 4×10^4 cps. A count rate sample segment obtained from the detectors' signal is shown in Fig. 2. More details on the experimental setup and acquisition systems can be found in (Geslot et al., 2015; Perret, 2015). The measurements analyzed in this paper are described in Table 2.

3. The power spectral density formalism

The transfer function of the reactor links the neutron noise (statistical fluctuations in the neutron flux around its mean value) to the neutron source fluctuations. The zero power transfer function can be derived from point kinetic equations, where the source noise is considered to be entirely due to fluctuations in the core's reactivity, in the neutron flux and in the precursors concentration (Keepin, 1965; Uhrig, 1970; Williams, 1974). For large enough frequencies, i.e. $\omega \gg \lambda_j$, the square of the amplitude of the zero power transfer function, $|H(\omega)|^2$, can be explicitly expressed in terms of the core's kinetic parameters in the following form (Santamarina et al., 2012)