Annals of Nuclear Energy 120 (2018) 691–706

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Determination of prompt neutron decay constant by time-domain fluctuation analyses of detector current signals

Yasunori Kitamura [a,*], Imre Pázsit [b], Tsuyoshi Misawa [a]

[a] Institute for Integrated Radiation and Nuclear Science, Kyoto University, Asashiro-Nishi, Kumatori-cho, Sennan-gun, Osaka 590-0494, Japan
[b] Department of Physics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

ARTICLE INFO

Article history:
Received 11 April 2018
Received in revised form 11 June 2018
Accepted 12 June 2018

Keywords:
Reactor noise
Time-domain analysis
Neutron detector current
Count-loss effect
Prompt neutron decay constant
Subcriticality
Auto-covariance function technique
Variance-to-mean function technique

ABSTRACT

The conventional time-domain reactor noise techniques analyse the number of neutron detector pulse signals, so that they sometimes encounter serious difficulties owing to the count-loss effect due to the dead time of detector systems. To avoid all the difficulties coming from the count-loss effect, a novel time-domain technique was recently proposed (Pál and Pázsit, 2015). This technique analyses the auto-covariance function of continuous current signals arising from ionization chambers such as the fission chamber, so that it is inherently insensitive to the count-loss effect. In the present study, a different time-domain technique that analyses the integral values of current signals is proposed. With regard to these two techniques, the experimental conditions under which they successfully measure the subcriticality through determination of the prompt neutron decay constant are clarified.

1. Introduction

The neutron population in subcritical reactor systems temporally fluctuates. This fluctuation phenomenon, referred to as the reactor noise, is useful because it involves several important reactor physics parameters. Various techniques that analyse the reactor noise have hence been developed so far to extract those parameters (de Hoffmann, 1949; Feynman et al., 1956; Orndoff, 1957; Thie, 1963; Pacilio, 1969; Saito, 1970; Uhrig, 1970; Seifritz and Stegemann, 1971; Otsuka, 1972; Williams, 1974; Pázsit and Pál, 2008).

From a criticality safety point of view, determination of the prompt neutron decay constant by the reactor noise techniques has attracted great interest, since it is directly related to subcriticality monitoring in the critical assemblies or the nuclear fuel cycle facilities (Albrecht, 1962; Edelmann et al., 1975; Misawa et al., 1990; Kitamura et al., 1999, 2000). In recent days, research activities for developing a subcriticality monitor that is desirable to be equipped in future accelerator-driven systems have been intensively pursued on the basis of the reactor noise techniques (Pázsit and Yamane, 1998, 1999; Yamane and Pázsit, 1998; Behringer and Wydler, 1999; Muñoz-Cobo et al., 2001; Degweker, 2003; Pázsit et al., 2005; Kitamura et al., 2005, 2006; Degweker and Rana, 2007; Pázsit and Pál, 2008; Rana and Degweker, 2009; Kitamura and Misawa, 2017).

The reactor noise techniques are generally classified into two categories; the techniques based on the frequency-domain analysis and those based on the time-domain one. The latter techniques analyse the number of pulse signals arising from neutron detectors such as the ^{3}He and the BF_3 proportional counters. Therefore, one often encounters serious difficulties in reactor systems with high counting rates, since one fails to acquire accurate numbers of pulse signals owing to the count-loss effect due to the dead time of neutron detector systems.

The straightforward solution would be to improve the time-domain techniques so as to give a robustness against the count-loss effect. Whereas the mean count rate is consequently underestimated in the presence of dead time, which is relatively straightforward to correct for, the variance can be both under- and overestimated, depending on the actual parameters of the system and the detection process, and a possible correction method is rather cumbersome. Indeed, several researchers have derived different formulae of the time-domain techniques with correction for the count-loss effect (Srinivasan, 1967; Srinivasan and Sahni, 1967; Edelmann et al., 1975; Yamane and Ito, 1996; Hashimoto et al., 1996; Hazama, 2003; Kitamura and Fukushima, 2015). On the other hand, Pál and Pázsit (2015) recently showed that there

* Corresponding author.
E-mail address: y-kitamura@rri.kyoto-u.ac.jp (Y. Kitamura).

https://doi.org/10.1016/j.anucene.2018.06.021
0306-4549/

Nomenclature

λ_s probability that one neutron undergoes a scattering reaction per unit time
λ_c probability that one neutron undergoes a capture reaction in the multiplying medium per unit time
λ_d probability that one neutron undergoes a detection reaction in the neutron detector per unit time
λ_f probability that one neutron undergoes a fission reaction in the multiplying medium per unit time
$p_f(n)$ probability that n neutrons are born in one fission reaction
$\langle \nu \rangle$ first moment of the number of neutrons per fission reaction
$\langle \nu(\nu-1) \rangle$ second factorial moment of the number of neutrons per fission reaction
ρ reactivity of the subcritical reactor system
Λ neutron generation time of the subcritical reactor system
α prompt neutron decay constant of the subcritical reactor system
S intensity of source events
$p_s(\gamma)$ probability that γ neutrons are born in one source event
$\langle \xi \rangle$ first moment of the number of neutrons per source event
$\langle \xi(\xi-1) \rangle$ second factorial moment of the number of neutrons per source event
$h(y_1, \theta_1, y_2, \theta_2, t)$ probability density function for observing detector current y_1 at time $t-\theta_1$ and current y_2 at time $t-\theta_2$ resulting from the detection of one single neutron at time 0
$\widetilde{h}(\omega_1, \theta_1, \omega_2, \theta_2, t)$ characteristic function of $h(y_1, \theta_1, y_2, \theta_2, t)$
$p(y_1, \theta_1, y_2, \theta_2, t)$ probability density function for observing detector current y_1 at time $t-\theta_1$ and current y_2 at time $t-\theta_2$ given rise by the injection of one single neutron into the subcritical reactor system at time 0
$\widetilde{p}(\omega_1, \theta_1, \omega_2, \theta_2, t)$ characteristic function of $p(y_1, \theta_1, y_2, \theta_2, t)$
$r_n(y_1, \theta_1, y_2, \theta_2, t)$ probability density function for observing current y_1 at time $t-\theta_1$ and current y_2 at time $t-\theta_2$ given rise by the simultaneous injection of n neutrons into the subcritical reactor system at time 0
$\widetilde{r}_n(\omega_1, \theta_1, \omega_2, \theta_2, t)$ characteristic function of $r_n(y_1, \theta_1, y_2, \theta_2, t)$
$P(y_1, \theta_1, y_2, \theta_2, t)$ probability density function for observing current y_1 at time $t-\theta_1$ and current y_2 at time $t-\theta_2$ given rise by switching on the external stationary neutron source at time 0
$\widetilde{P}(\omega_1, \theta_1, \omega_2, \theta_2, t)$ characteristic function of $P(y_1, \theta_1, y_2, \theta_2, t)$
α_e time constant of neutron detector system
ε ratio of α_e to α

is another solution for avoiding the difficulties arising from the count-loss effect. They paid attention to continuous current signals arising from ionization chambers such as the fission chamber, and elaborated the theory of neutron correlation in current signals on the basis of the backward master equation formalism (Pál, 1958; Bell, 1965). By using the theory thus obtained, they proposed a novel time-domain technique. This technique analyses the auto-covariance function of current signals, so that it is inherently insensitive to the count-loss effect.

In the present study, the theory of neutron correlation in current signals is extended to include multiple neutron emission sources (such as the ^{252}Cf spontaneous fission source) that are often employed (Furuhashi and Inaba, 1966; Pázsit and Yamane, 1998, 1999; Yamane and Pázsit, 1998; Pázsit, 1999). On the basis of the theory thus developed, an alternative time-domain technique is proposed, which analyses the first two moments of the *integral values* of current signals to provide another option. Furthermore, with regard to these two techniques, the experimental conditions under which they work are discussed to apply them to subcriticality measurement through determination of the prompt neutron decay constant.

In the next section, the notations employed in the present study are introduced. Sections 3 and 4 are devoted to the theory of correlations in neutron detector current signals that accounts for the multiple neutron emission source. The new time-domain technique that analyses the integral values of current signals is proposed in Section 5. Finally, the conclusion is summarized in Section 7 on the basis of the discussions given in Section 6.

2. Notations

2.1. Subcritical reactor system

In the present study, a mono-energy one-point reactor model will be used throughout, for a simple discussion. Delayed neutrons are neglected, while their effect will be separately discussed in a forthcoming communication.

A zero-power subcritical reactor system that consists of a multiplying medium, a neutron detector, and an external stationary neutron source is supposed. The neutron interactions in the subcritical reactor system (i.e., scattering, capture, detection, and fission) are described with the following reaction intensities:

$$\lambda_x = v\Sigma_x, \quad x = s, c, d, f, \tag{1}$$

$$\lambda_a = \lambda_c + \lambda_d + \lambda_f, \tag{2}$$

where λ_s is the probability that one neutron undergoes a scattering reaction per unit time, λ_c the probability that one neutron undergoes a capture reaction in the multiplying medium per unit time, λ_d the probability that one neutron undergoes a detection reaction in the neutron detector per unit time, λ_f the probability that one neutron undergoes a fission reaction in the multiplying medium per unit time, Σ_x the macroscopic cross-section with respect to the neutron interaction x (= s, c, d, f), and v the velocity of neutrons.

The probability distribution that n neutrons are born in one fission reaction is denoted by

$$p_f(n), \tag{3}$$

with

$$\sum_{n=0}^{+\infty} p_f(n) = 1. \tag{4}$$

Using this probability, the first two factorial moments of the number of neutrons per fission reaction are given as

$$\langle \nu \rangle = \sum_{n=0}^{+\infty} n p_f(n), \tag{5}$$

$$\langle \nu(\nu-1) \rangle = \sum_{n=0}^{+\infty} n(n-1) p_f(n). \tag{6}$$