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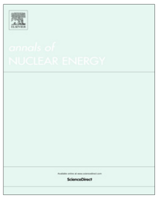

Delayed neutron effect in time-domain fluctuation analyses of neutron detector current signals

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ABSTRACT

In the previous study, the theoretical formulae of two time-domain reactor noise techniques, i.e., the auto-covariance and the variance-to-mean function techniques, were derived (Kitamura et al., 2018). These two techniques analyse the temporal fluctuation in continuous neutron detector current signals arising from ionization chambers such as the fission chamber. They are hence inherently insensitive to the count-loss effect that sometimes brings serious difficulties to the conventional time-domain techniques that analyse the number of detector pulse signals. With regard to these two techniques, the experimental conditions under which they successfully measure the subcriticality through determination of the prompt neutron decay constant were clarified. However, for mathematical simplicity and the sake of insight, the previous study was performed on the basis of a theoretical model neglecting delayed neutrons. The formulae of these two techniques are hence re-derived by taking delayed neutrons into consideration. Using the formulae thus derived, the delayed neutron effect in these two techniques is discussed.

1. Introduction

It is known that several important reactor physics parameters are involved with the reactor noise. 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). Especially 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 the subcriticality monitoring in critical assemblies, nuclear fuel cycle facilities, and future accelerator-driven systems (Albrecht, 1962; Edelmann et al., 1975; Misawa et al., 1990; Pázsit and Yamane, 1998, 1999; Yamane and Pázsit, 1998; Behringer and Wydler, 1999; Kitamura et al., 1999, 2000, 2005, 2006; Muñoz-Cobo et al., 2001; Degweker, 2003; Pázsit et al., 2005; Degweker and Rana, 2007; 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 neutron detector 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 higher 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 (Srinivasan, 1967; Srinivasan and Sahni, 1967; Edelmann et al., 1975; Yamane and Ito, 1996; Hashimoto et al., 1996; Hazama, 2003; Kitamura and Fukushima, 2014). 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. On the other hand, Pál and Pázsit (2015, 2016) recently showed that there is another solution for overcoming or rather cleverly avoiding the difficulties coming from the count-loss effect. They paid attention to continuous current signals arising from ionization chambers such as the fission chamber that are inherently insensitive to the count-loss effect, and elaborated the theory of neutron correlations 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, i.e., the auto-covariance function technique.

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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.
$p_f(n,c)$	probability that n prompt neutrons and c delayed neutron precursors are simultaneously born in one fission reaction.
$\langle\nu_p\rangle$	first moment of the number of prompt neutrons per fission reaction.
$\langle\nu_d\rangle$	first moment of the number of delayed neutrons per fission reaction.
$\langle\nu\rangle$	first moment of the number of total neutrons per fission reaction.
$\langle\nu_p(\nu_p-1)\rangle$	second factorial moment of the number of prompt neutrons per fission reaction.
$\langle\nu_p\nu_d\rangle$	second moment of the product of prompt and delayed neutron numbers per fission reaction.
$\langle\nu_d(\nu_d-1)\rangle$	second factorial moment of the number of delayed neutrons per fission reaction.
$\langle\nu(\nu-1)\rangle$	second factorial moment of the number of total 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.
β	delayed neutron fraction of the subcritical reactor system.
λ	delayed neutron time 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 the detector current value y_1 at time $t-\theta_1$ and the current value y_2 at time $t-\theta_2$ resulting from the detection of one single neutron at time 0.
$\tilde{h}(\omega_1,\theta_1,\omega_2,\theta_2,t)$	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 the detector current value y_1 at time $t-\theta_1$ and the current value y_2 at time $t-\theta_2$ due to the injection of one single neutron into the subcritical reactor system at time 0.
$\tilde{p}(\omega_1,\theta_1,\omega_2,\theta_2,t)$	characteristic function of $p(y_1,\theta_1,y_2,\theta_2,t)$.
$q(y_1,\theta_1,y_2,\theta_2,t)$	probability density function for observing the detector current value y_1 at time $t-\theta_1$ and the current value y_2 at time $t-\theta_2$ due to the injection of one single delayed neutron precursor into the subcritical reactor system at time 0.
$\tilde{q}(\omega_1,\theta_1,\omega_2,\theta_2,t)$	characteristic function of $q(y_1,\theta_1,y_2,\theta_2,t)$.
$r_{n,c}(y_1,\theta_1,y_2,\theta_2,t)$	probability density function for observing the detector current value y_1 at time $t-\theta_1$ and the current value y_2 at time $t-\theta_2$ due to the simultaneous injection of n neutrons and c delayed neutron precursors into the subcritical reactor system at time 0.
$\tilde{r}_{n,c}(\omega_1,\theta_1,\omega_2,\theta_2,t)$	characteristic function of $r_{n,c}(y_1,\theta_1,y_2,\theta_2,t)$.
$P(y_1,\theta_1,y_2,\theta_2,t)$	probability density function for observing the current value y_1 at time $t-\theta_1$ and the current value y_2 at time $t-\theta_2$ given rise by switching on the external stationary neutron source at time 0.
$\tilde{P}(\omega_1,\theta_1,\omega_2,\theta_2,t)$	characteristic function of $P(y_1,\theta_1,y_2,\theta_2,t)$.
α_p	larger time constant involved in general solutions of one-point reactor kinetic equation considering one-grouped delayed neutrons.
α_d	smaller time constant involved in general solutions of one-point reactor kinetic equation considering one-grouped delayed neutrons.
α_e	time constant of neutron detector system.
Δ_2	enhancement factor of second order moments of neutron correlations, generated by branching (or multiplication in fission chain), due to multiplicity of neutrons born in one source event.

In the previous study (Kitamura et al., 2018), the theory of neutron correlations in current signals was 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 obtained, the formulae of the auto-covariance function technique and a different time-domain one that analyses the first two moments of the integral values of current signals, i.e., the variance-to-mean function technique, were derived. Furthermore, with regard to these two techniques, the experimental conditions under which they successfully work were investigated to apply them to subcriticality measurement through determination of the prompt neutron decay constant. As a result, it was clarified that the prompt neutron decay constant could be determined when the time constant of neutron detector systems with enough high detector efficiencies is much larger than the prompt neutron decay constant. However, for mathematical simplicity and the sake of insight, the previous study was performed on the basis of a theoretical model neglecting delayed neutrons. In the present study, the formulae of these two techniques are hence re-derived by taking delayed neutrons into consideration. Using the formulae thus derived, the delayed neutron effect in these two techniques is discussed.

In the next section, the notations employed in the present study are introduced. By taking delayed neutrons into consideration, the theory of neutron correlations in current signals is developed in Sections 3 and 4. On the basis of the theory thus developed, the formulae of the auto-covariance and the variance-to-mean function techniques are derived in Section 5. Finally, the conclusion is summarized in Section 7 on the basis of the discussions given in Section 6.