Annals of Nuclear Energy 118 (2018) 92–98

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Application of advanced Rossi-alpha technique to reactivity measurements at Kyoto University Critical Assembly

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A R T I C L E   I N F O

Article history:
Received 2 January 2018
Received in revised form 4 April 2018
Accepted 5 April 2018

Keywords:
Advanced Rossi-alpha
Detector count signals
Nuclear research reactor
Fyenman-alpha
Rossi-alpha

A B S T R A C T

This study presents the first application of the advanced Rossi-alpha method (theoretically introduced by Kong et al., 2014) on the reactivity measurements in a research reactor: detector count signals at the Kyoto University Critical Assembly (KUCA) facility. The detector signals in the KUCA A-type core are analyzed by three subcriticality measurement methods: (1) Feynman-alpha (F-α) method, (2) Rossi-alpha (R-α) method, and (3) advanced Rossi-alpha (advanced R-α) method. Four cases are analyzed for two different subcritical states of the core and two different neutron source locations. Two different negative reactivity ρ values are obtained by the measurements of control rod worth and regarded as the reference reactivity values, comparing the results by the four methods.

The F-α shows reactivity errors ranging between 7.1 and 7.3% due to its use of variance-to-mean ratios of detector count signals, which are not very sensitive to neutron background noise. However, the fitting uncertainties associated to the F-α results are large, ranging between 5.4 and 12.8% at one standard deviation. The R-α shows small fitting uncertainties ranging between 2.8 and 3.8%, although reactivity errors are in the range of 3.5–26.5% due to the neutron background noise. Finally, the advanced R-α that explicitly models the neutron background noise contrary to the previous methods shows the reactivity errors in the range of 1.0–11.8%, and provides the lowest uncertainties of the measured ρ in the range of 0.4–0.9%. In conclusion, among the four methods applied to the reactivity measurements at KUCA, the advanced R-α reveals the best accuracy with the lowest uncertainties.

1. Introduction

Experiments conducted in research reactors are crucial to increase our knowledge of nuclear physics and validate reactor analysis codes and methods. In early 2017, the Kyoto University Critical Assembly (KUCA) facility has reopened after its safety equipment was reinforced to satisfy the stricter nuclear regulations in Japan consecutively to the Fukushima accident. Using the KUCA facility, we carried out subcriticality measurement experiments and analyzed the experimental results with different methods to investigate and compare the reliability of each method. The three subcriticality measurement methods used in this study are (1) the Feynman-alpha (F-α) method, (2) the Rossi-alpha (R-α) method, and (3) the advanced Rossi-alpha (advanced R-α) method.

After reopening of the KUCA facility, experiments on reactivity measurements have been carried out at the polyethylene-moderated core (A-core) in Kyoto University Research Reactor Institute (Pyeon et al., 2017a, 2017b). The KUCA A-core has been mainly engaged in a feasibility study on the accelerator-driven system (ADS) (Van et al., 2017; Zheng et al., 2017), and this study is focusing on improvement of subcriticality measurement in a core system. This research differs from the previous experiments in the way that (1) a new core configuration is investigated, different from previous KUCA core configurations and (2) a state-of-the-art technique (advanced R-α method; proposed by Kong et al., 2014) is applied for the first time to neutron count signals obtained from the detectors. The advanced R-α method was applied for only virtual signals generated by Monte Carlo real-time simulation. The

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https://doi.org/10.1016/j.anucene.2018.04.009
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objective of this study is to evaluate performance of the advanced R-α method on the real neutron signals in comparison with those of the traditional R-α and F-α methods.

The structure of this paper is as follows: Section 2 describes the underlying principles behind the three measurement methods applied to the reactivity measurements at KUCA. Section 3 introduces the configuration of the core and the cases analyzed by the three methods. Section 4 describes the results of experimental analyses by three methods using the measured data. Section 5 concludes this paper.

2. Theory

2.1. Feynman-alpha method

The F-α method uses the principle that the variance-to-mean ratio of detector count signals is theoretically equal to a unit when delayed neutrons are neglected. When the effect of delayed neutrons is taken into account, the variance-to-mean ratio of detector count signals follows the Poisson's distribution (Taninaka et al., 2011).

Eq. (1) expresses the variance-to-mean ratio of the detector signals (Tonoike et al., 2004).

$$Y = \frac{\overline{C^2} - \bar{C}^2}{\bar{C}} = Y_\infty\left(1 - \frac{1 - e^{-\alpha(t_2 - t_1)}}{\alpha(t_2 - t_1)}\right) + N. \quad (1)$$

In Eq. (1), Y is the variance-to-mean ratio of the detector counts in the time range (t_2-t_1), t_1 and t_2 are start and end times of a gate time, Y_∞ is the saturated correlation amplitude, α is the neutron decay constant, and N is a coefficient. Y_∞, N, and α can be determined by least square fitting of the detector count signals. After the decay constant α is determined, the reactivity ρ is calculated by Eq. (2) where β is the delayed neutron fraction, and Λ is the neutron generation time.

$$\alpha = \frac{\beta - \rho}{\Lambda}; \quad \rho = \beta - \alpha\Lambda. \quad (2)$$

Usually, the delayed neutron fraction β has values of 3∼5% (Rais et al., 2016). In this study, the measured β and Λ were provided by the professional KUCA staffs as 0.00853 and 3.33e−5s, respectively.

2.2. Rossi-alpha method

In the R-α method, it is important to distinguish the neutrons correlated by neutron chain reactions and the random neutrons from background noise (Sun et al., 2017). The R-α method uses the correlation between prompt neutrons at time t_0 and at time $t_0 + \Delta t$. The neutrons detected at time $t_0 + \Delta t$ can be divided into two categories: neutrons from neutron chain reactions generated by neutrons at time t_0 and neutrons from background noise including prompt and delayed neutrons.

The probability of detecting correlated neutron can be expressed in Eq. (3) using the average fission rate F (Hansen, 1985).

$$p(t_1, t_2) = F^2\varepsilon^2 + F\varepsilon^2\frac{D_v(1-\beta)^2}{2(\beta - \rho)\Lambda}e^{-\alpha(t_2 - t_1)}. \quad (3)$$

In Eq. (3), $p(t_1,t_2)$ is the probability that neutrons detected at time t_1 are related to neutrons detected at time $t_2 > t_1$, F is the average fission rate of the whole core, and D_v is the so-called Diven's factor. The terms β, Λ, and α are the defined as in Eq. (2).

Eq. (4) can be written in the following way:

$$p(t_1, t_2) = ae^{-b(t_2 - t_1)} + c; \quad \alpha = b. \quad (4)$$

In Eq. (4), a, b, and c are coefficients that can be determined by the least square fitting of the detector count signals, given that the signals have been arranged beforehand in order of the time differences, which means that the x-axis is (t_2-t_1), so that they can be presented as the exponential form of Eq. (4). After getting the decay constant α by least square fitting, the reactivity ρ is calculated by Eq. (2).

2.3. Advanced Rossi-alpha method

The advanced R-α method adds to the R-α equation in Eq. (3) a term which considers the random noise of the system. The probability of detecting correlated neutron from Eq. (3) is now expressed as Eq. (5) in the advanced R-α formulation (Kong et al., 2014).

$$p(t_1, t_2) = F^2\varepsilon^2 + F\varepsilon^2\frac{D_v(1-\beta)^2}{2(\beta - \rho)\Lambda}e^{-\alpha(t_2 - t_1)} + 4R^2\xi_1\xi_2 + 2R(\xi_1 + \xi_2)F\varepsilon. \quad (5)$$

In Eq. (5), the uncorrelated neutron detection is expressed with random numbers ξ_1 and ξ_2, whereas the R-α formulation treats the uncorrelated term as a constant. The advanced R-α formulation assumes that the uncorrelated neutron detection has uniform distribution. In Eq. (5), R is the magnitude of random noise and ξ_1 and ξ_2 are random numbers uniformly sampled between 0 and 1. Eq. (5) can be simplified to Eq. (6).

$$p(t_1, t_2) = a_{r-\alpha} \times e^{-b(t_2 - t_1)} + c_{r-\alpha} + \frac{4}{3}R(1 - 2\xi_1)(1 - 2\xi_2) + 2R(2 - 2\xi_1 - 2\xi_2); \alpha = b. \quad (6)$$

In Eq. (6), $a_{r\text{-}\alpha}$, b, $c_{r\text{-}\alpha}$, and R are coefficients, and ξ_1 and ξ_2 are random numbers uniformly sampled between 0 and 1. Among these coefficients, $a_{r\text{-}\alpha}$ and $c_{r\text{-}\alpha}$, come from the R-α fitting. R can be expressed as a function of time interval as in Eq. (7).

$$R(t_2 - t_1) = \frac{R_0}{t_2 - t_1}. \quad (7)$$

In Eq. (7), R_0 is a constant accounting for non-correlated neutron noise magnitude. These random noises whose magnitude is between 0 and R_0 are contaminated to the correlated neutron detection. In Eq. (6), the coefficient b (=α) is determined by the least square fitting using $a_{r\text{-}\alpha}$, $c_{r\text{-}\alpha}$, R, ξ_1, and ξ_2. The analysis is repeated 1000 times (i.e. ξ_1 and ξ_2 are sampled 1000 times and the least square fitting is conducted 1000 times) to obtain average and standard deviation of α values. After obtaining the average α value, the reactivity ρ is calculated by Eq. (2).

3. Description of KUCA facility and experiment

The KUCA facility was established in 1974 for nuclear reactor physics experiments. It is composed of three types of cores: two of them are solid-moderated cores (A-core and B-core), and the other is light-water-moderated core (C-core) (Misawa et al., 2010). The three cores are operated at very low power and therefore the nuclear fuel can always be considered as fresh fuel. The subcriticality of the cores is determined by the thickness and the arrangement of fuel and moderator plates.

3.1. KUCA facility configuration

Fig. 1 shows the configuration of the A-core used for subcritical measurement experiments.

In Fig. 1, F indicates the normal fuel assembly composed of uranium and polyethylene, f indicates the special fuel assembly composed of uranium, polyethylene, and lead, p indicates the polyethylene moderator assembly, C1∼C3 indicate the positions of the control rods, S4∼S6 indicate the positions of the safety rods, N indicates the Am-Be neutron source, FC indicate the fission chambers, and Gr indicates graphite. The core is composed in total