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Deconvolution-based real-time neutron flux reconstruction for Self-Powered Neutron Detector

Qingmin Zhang[a,b,*], Bangjie Deng[a], Xinxin Liu[a], Chengyuan Li[a], Yaodong Sang[a], Liangzhi Cao[a,b], Guangwen Bi[c], Chuntao Tang[c], Peng Zhang[d], Dayin Tong[a], Yang Li[a]

[a] Department of Nuclear Science and Technology, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Shaanxi Key Laboratory of Advanced Nuclear Energy and Technology, Xi'an Jiaotong University, Xi'an 710049, China
[c] Shanghai Nuclear Engineering Research and Design Institute, Shanghai 200233, China
[d] Sino Shaanxi Nuclear Industry Group, Xi'an 710100, China

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ABSTRACT

Self-Powered Neutron Detector (SPND) is useful for in-core neutron flux measurement in nuclear reactors due to its tiny size, simple structure, ruggedness and self-powered feature. One type of SPNDs with delayed current from instable intermediate nuclides cannot directly represent the real-time in-core neutron flux $\Phi(t)$ by their current $I(t)$, which should be avoided during reactor control and protection. In this paper, we proposed a deconvolution-based method to reconstruct real-time neutron flux for SPND. Following the establishment of dynamic model, the unit-impulse response function $h(t)$ was easily obtained when neutron flux was unit-impulse. Then, the iterative compensation relations were established for delay compensation according to the convolution relationship $I(t) = \Phi(t) * h(t)$. In the meanwhile, determination methods for initial values were also proposed and the compensation performance for jump neutron flux was demonstrated to be only 0.3 s. Furthermore, the dependences on initial conditions and sampling time interval were studied systematically, indicating our method is effective and robust. Finally, our method has been compared with a typical compensation method and validated with measured current, showing its advantages. This method is very attractive due to its obvious simplicity, high intuitiveness and general applicability.

1. Introduction

Reactor in-core is a severe environment due to its high temperature, high pressure and strong radiation, and Self-Powered Neutron Detectors (SPNDs) have been widely applied for measuring in-core neutron flux distribution (Ma and Jiang, 2011) because of their excellent advantages: compactness, simplicity, no-HV supply and ruggedness (Todt, 1996). SPNDs are generally classified into two types according to neutron reaction with their emitter materials. For the first type, their current is prompt to neutron flux (^{59}Co, ^{195}Pt, $^{180}HfO_2$), while for the second type, their current has delayed component (^{103}Rh, ^{51}V, ^{107}Ag, ^{109}Ag) (Goldstein and Todt, 1979). The decay schemes for prompt SPNDs are very simple and the current is only attributed to the electrons from γ rays generated by (n, γ) reactions, while the decay schemes for SPNDs with prompt current and delayed current are complicated and the delayed current is contributed by the electrons from γ or β rays generated by the intermediate nuclides' de-excitation or decays (Todt, 1996).

To avoid the response delay, quite a few dynamic compensation methods have been developed. Analog compensation based on inverse function amplifier (Hoppe and Maletti, 1992) is a very direct method, but the parameters of the circuit elements cannot be changed flexibly considering SPND's burning-up. Transfer function combined with digital compensation has obtained good effect (Mishra et al., 2014). Approximation and discretization are introduced to solve the origin governing equations analytically, giving an improved response delay of 2 s (Kulacsy and Lux, 1997). A linear matrix inequality based method in the worst-case estimation error sense has minimized the response delay to 1.4 s (Park et al., 1999). It's worth mentioning that these compensated response delays depend on specific cases and cannot be compared directly. On the other hand, all the methods mentioned above are not intuitive and not easy to be transplanted into other SPNDs. Recently, a simple iterative method has been developed, showing its simplicity and effectiveness (Zhang et al., 2017), however it doesn't have the ability to predict ideal SPND current curve for known neutron flux curve.

Accordingly, a deconvolution-based compensation method with

* Corresponding author at: Department of Nuclear Science and Technology, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail address: zhangqingmin@mail.xjtu.edu.cn (Q. Zhang).

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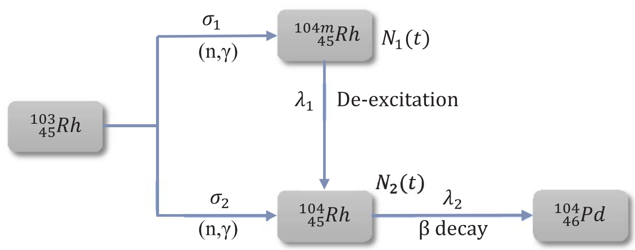

Fig. 1. The decay scheme of neutron reaction with ^{103}Rh (Zhang et al., 2017).

high intuitiveness and strong applicability was proposed and demonstrated in this paper.

2. Method description

As a typical representative SPND with delayed current, Rhodium SPND is favorable to be used for neutron flux mapping in light water reactor due to its relatively high sensitivity to neutrons and relatively low sensitivity to gammas, however, its delayed current due to intermediate nuclides with half-life results is a big problem for applying it in reactor control and protection system (Todt, 1996). So Rh SPND was chosen to demonstrate our deconvolution-based compensation method.

2.1. Dynamic equations

All compensation methods have to start with the establishment of dynamic model in the basis of decay scheme of neutron reactions with emitter materials and SPND current's production mechanism.

The decay scheme of neutron reaction with ^{103}Rh shown in Fig. 1 (Zhang et al., 2017, Banda, 1976, Neutron Activation Properties of Isotopes Useful for Neutron Activation Analysis, 2017). When thermal neutrons are captured on ^{103}Rh nuclei, ^{104m}Rh (^{104}Rh) nuclei are produced and γ rays are directly emitted in the same time. Then ^{104m}Rh nuclei de-excite to ^{104}Rh nuclei with emission of γ rays in decay constant λ_1, while ^{104}Rh nuclei from ^{103}Rh (n, γ) reaction and ^{104m}Rh de-excitation decay to ^{104}Pd with decay constant $\lambda_{2,}$ emitting β and γ rays.

SPND's current is the flow of the electrons, which are generated from β and γ rays mentioned above in insulator or emitter, and then are collected by collector (Neutron Detectors And Reactor Instrumentation, 2017). Obviously, the ideal current of Rh SPND consists of prompt current and delayed current: (1) Prompt current is attributed to the secondary electrons from γ rays, which are directly generated in (n, γ) reactions; (2) There are two delayed components. One is contributed by secondary electrons from γ rays directly emitted in the process of ^{104m}Rh de-excitation; the other one is attributed to secondary electrons from γ rays and β rays, which are generated in the process of ^{104}Rh's decay to ^{104}Pd. Considering that β and γ rays interacts with material promptly, the total SPND current can be written naturally in Eq. (1).

$$\mathrm{I(t)} = (f_1\sigma_1 + f_2\sigma_2)N_{Rh}^{103}\Phi(\mathrm{t}) + j_1\lambda_1N_1(t) + j_2\lambda_2N_2(t) \tag{1}$$

Where

$\phi(t)$ neutron flux
N_{Rh}^{103} the atomic density of ^{103}Rh
$N_1(t)$ the atomic density of ^{104m}Rh
$N_2(t)$ the atomic density of ^{104}Rh
σ_1 microscopic absorption cross section of ^{103}Rh (n, γ) interaction to ^{104m}Rh
σ_2 microscopic absorption cross section of ^{103}Rh (n, γ) interaction to ^{104}Rh
λ_1 decay constant of ^{104m}Rh
λ_2 decay constant of ^{104}Rh
f_1 prompt current coefficient for γ from ^{103}Rh (n, γ) interaction to ^{104m}Rh
f_2 prompt current coefficient for γ from ^{103}Rh (n, γ) interaction to ^{104}Rh
j_1 delayed current coefficient for γ from ^{104m}Rh's de-excitation
j_2 delayed current coefficient for β from ^{104}Rh β decay
I(t) SPND current

It's reasonably assumed that the atom density of ^{103}Rh is constant during compensation due to its very little burning-up rate (Todt, 1996). Because interaction cross section is different for β and γ, even for same particles with different energies, current coefficients are introduced to describe the abilities that radiations from a given process are converted to current. Obviously, current coefficients are different for detectors with different geometries.

Macroscopic absorption cross sections $\Sigma_1 = \sigma_1N_{Rh}^{103}$,$\Sigma_2 = \sigma_2N_{Rh}^{103}$ are introduced, Eq. (1) can be written in the following form.

$$\mathrm{I(t)} = (f_1\Sigma_1 + f_2\Sigma_2)\Phi(\mathrm{t}) + j_1\lambda_1N_1(t) + j_2\lambda_2N_2(t) \tag{2}$$

From Eq. (2) we can know $S = f_1\Sigma_1 + f_2\Sigma_2$ is the prompt sensitivity coefficient of SPND to the prompt neutron flux. Also, as indicated in Eq. (2), it's obviously seen that the delayed component are controlled by the numbers of ^{104m}Rh and ^{104}Rh. Hence, the dynamic equations of intermediate nuclides ^{104m}Rh and ^{104}Rh should be established for compensation purpose. Based on Fig. 1, differential equations for ^{104m}Rh and ^{104}Rh can be easily written as below.

$$\frac{\mathrm{d}N_1(t)}{\mathrm{dt}} = \Sigma_1\Phi(\mathrm{t}) - \lambda_1N_1(t) \tag{3}$$

$$\frac{\mathrm{d}N_2(t)}{\mathrm{dt}} = \Sigma_2\Phi(\mathrm{t}) + \lambda_1N_1(t) - \lambda_2N_2(t) \tag{4}$$

So Eqs. (2)(4) are complete to describe the problem. In the following study, the values of the parameters are chosen as below unless others specified. The decay-related parameters are from the reference (Zhang et al., 2017) and the parameters related to detector dimensions were updated to make them be more like a realistic detector, such as the ratio of prompt current is typically in the range from 5 to 15% (Li and Xia, 2009).

$\Sigma_1 = 0.8165\ \mathrm{cm}^{-1}$;

$\Sigma_2 = 10.0207\ \mathrm{cm}^{-1}$

$\lambda_1 = 0.00268\ \mathrm{s}^{-1}$

$\lambda_2 = 0.01650\ \mathrm{s}^{-1}$

$\lambda_2 = 0.01650\ \mathrm{s}^{-1}$

$j_1 = 4.583 \times 10^{-22}\ \mathrm{A{\cdot}s{\cdot}cm^3}$

$j_2 = 5.956 \times 10^{-21}\ \mathrm{A{\cdot}s{\cdot}cm^3}$

$S = f_1\Sigma_1 + f_2\Sigma_2 = 3.6 \times 10^{-21}\ \mathrm{A{\cdot}s{\cdot}cm^2}$

2.2. Unit impulse response

This is a dynamical system with input *Φ(t)* and output *I(t)*, which is obviously a linear time-invariant system. One way to characterize a linear time-invariant system is to measure its impulse response function. For a small pulse of unit amplitude δ(t) as described in Eq. (5), its response is called unit impulse response function h(t), and then I(t) can be expressed by the convolution of Φ(t) and h(t) as shown in Eq. (6) (Linear time-invariant systems and convolution, 2017).

$$\delta(t) = \begin{cases} 1 & (t = 0) \\ 0 & (t \neq 0) \end{cases} \tag{5}$$

$$I(t) = \Phi(t) * h(t) \tag{6}$$

For Φ(t) = δ(t), Eqs. (2)(4) can be written as below.