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New findings on neutron noise propagation properties in void containing water using neutron noise transport calculations

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ABSTRACT

This paper presents new findings in predicting the void fraction or void transit time of void-containing water flow using the results of multi-group neutron noise transport calculations. The neutron noise transport equation in the frequency domain is solved with a recently developed Monte Carlo method that uses complex-valued weights. In the calculations, the noise of thermal neutrons that penetrates a two-dimensional channel of void-containing water is obtained to predict the void properties. The thermal neutron noise is influenced by the slow down from the neutron noise in the higher energy range and by the transport of the thermal neutron noise. This influence becomes more notable in a lower void fraction or in a wider water channel. If the thickness of the channel is small enough, the void transit time can be accurately predicted using the CPSD between detector pairs aligned in the flow direction. In a wider channel, an anomalous void transit time would be obtained from the CPSD. The results of the multi-group calculation show that the APSD in a lower void fraction deviates from the Lorentzian form that holds in the one-energy group approximation. This deviation is caused by the higher energy neutron noise, whose frequency characteristics are different from the thermal neutron noise. Assuming that the one-energy group approximation is applicable, the relationship between the break frequency of the APSD and the neutron diffusion length or neutron age is clearly observed, which suggests that the measurement of the APSD could lead to the prediction of void properties.

1. Introduction

There have been many studies on techniques using neutron noise for measuring a coolant/moderator flow velocity profile and other two-phase flow properties in voided water (Kosály, 1980; Kosály et al., 1982; Pázsit and Demazière, 2010; Pázsit and Dykin, 2010; Dykin and Pázsit, 2013). These studies mainly focus on the diagnostics of boiling water reactors (BWRs) using in-core monitors such as the local power range monitors (LPRMs) and the traversing in-core probe (TIP). A void transit time in a channel of a BWR can be obtained from measuring the cross power spectral density (CPSD) of neutron noise between two vertically aligned neutron detectors. The measurement technique of a local void fraction in a BWR core has long been a challenging issue in terms of core diagnostics (Loberg et al., 2010). A technique that predicts a local void fraction uses the relationship between the break frequency of the auto power spectrum density (APSD) of measured neutron noise and the neutronic parameters (Kosály, 1980; Dykin and Pázsit, 2013). The neutronic parameters are related to the diffusion length of neutron noise that depends on the local void fraction. Thus, measuring the break frequency of an APSD provides useful information on the local void fraction. In this way, the neutron noise measurement techniques provide useful insight into nuclear reactor control and diagnostics.

The flux fluctuation in a neutron detector is driven by many noise sources. One of them is the mechanical vibration of a core structure such as a core barrel, fuel assemblies, and control rods. Another source is the fluctuation of thermal-hydraulic properties such as flow rate, temperature, and void fraction. The thermal-hydraulic fluctuation changes the nearby neutron detector signal by changing the neutron transport properties. In addition, the overall reactivity change of the reactor is affected by the fluctuation of the thermal-hydraulic properties, thereby producing additional neutron noise. The former neutron noise is referred to as a "local component", and the latter neutron noise is referred to as a "global component". It is important to have quantitatively accurate

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information on how the fluctuations of mechanical and thermal-hydraulic properties in a power reactor (*i.e.*, local component) cause the changes in the signals of neutron detectors. The region of interest regarding the local component of the neutron noise extends at most to one or two fuel assembly sizes when considering the neutron's mean free path in a light water reactor core. We need to direct our interest towards the behavior of neutron transport within a relatively short distance. Studies on neutron noise propagation in a reactor core have been published in many literature works. In these studies, the neutron noise propagations were analyzed by solving the diffusion equation for neutron noise (Behringer et al., 1977; Pázsit and Demazière, 2010). Another approach is to introduce the transport theory into neutron noise propagation analyses for quantitatively accurate analyses. A transport equation for neutron noise can be described in the same manner as the equation for neutron flux. Introducing the transport theory is advantageous in investigating the fine structure of the neutron noise propagation around an in-core detector.

The attempt that introduces the transport theory for calculating the neutron noise propagation was performed by the author of this paper (Yamamoto, 2013). In the paper, the frequency domain transport equation for neutron noise was solved with the Monte Carlo method by using the complex-valued weight technique. The results of this paper show that the difference in the neutron noise between the diffusion theory and the transport theory becomes remarkable near the noise source.

The noise source induced by the void formation in a BWR core is generated in the water coolant/moderator region within the channel boxes of fuel assemblies. Complicated fine structures exist between a neutron detector and the region of the noise source. The neutron noise is absorbed or scattered by the channel box, the water gap, and the sheath of the neutron detectors. Thus, the Monte Carlo method can be a favorable way to incorporate these complicated structures in the transport calculations for neutron noise.

The complex-valued weight Monte Carlo method was introduced to implement the B_1 approximation method and to generate diffusion coefficients for a fuel assembly (Yamamoto, 2012). The complex-valued weight Monte Carlo method was applied to solve the frequency domain transport equation of neutron noise (Yamamoto, 2013, 2014). In the paper (Yamamoto, 2014), the author developed a Monte Carlo method to address the frequency domain transport equation of neutron noise generated by void formation that moves upward in the rectangular channel of water. The distribution of neutron noise generated by the propagating perturbation due to an upward-moving void was calculated using the complex-valued weight Monte Carlo method in the paper (Yamamoto, 2014). The cross power spectral density (CPSD) was calculated using the neutron noises obtained in two vertically aligned locations to deduce the void transit time or void velocity. Another paper (Pettersen et al., 2015) addressed the development of a method for performing Monte Carlo calculations with the effect of stationary fluctuations on the neutron flux in macroscopic cross sections. According to the paper, the proposed method does not require any modification of the existing Monte Carlo code.

In the paper by Dykin and Pázsit (2013), a simple two-dimensional model of the random bubbly flow in a BWR heated channel was constructed to simulate the flow-induced neutron noise detector signals. A Monte Carlo methodology was used to construct realizations of the flow by positioning equi-diameter bubbles randomly in the two-dimensional flow channel. The normalized neutron noise is calculated through the spatial convolution between the void fraction and the local component of the transfer function as (Dykin and Pázsit, 2013):

$$\frac{\delta\varphi(z,t)}{\varphi_0(z)} = \int_0^H \exp(-\lambda(z)|z-z'|)\delta\alpha(z',t)dz' \tag{1}$$

where $\varphi_0(z)$= static flux, $\delta\varphi(z,t)$= neutron noise due to void fraction fluctuations, $\delta\alpha(z',t)$ = simulated void fraction signal at axial position z', and $\lambda(z)$= spatial decay constant of the local component. Eq. (1) assumes that the void velocity $V(z)$ and the static flux $\varphi_0(z)$ can be considered constant within the range $\lambda(z)^{-1}$. Fourier transforming $\delta\varphi(z,t)/\varphi_0(z)$ in Eq. (1) yields the normalized APSD $\left|\delta\varphi(z,\omega)/\varphi_0(z)\right|^2$. On the other hand, by assuming the propagating character of the void fluctuations as Eq. (16) in Dykin and Pázsit (2013):

$$\delta\alpha(z',\omega) \propto \exp\left(-\frac{i\omega}{V(z')}z'\right), \tag{2}$$

and the normalized APSD is given by

$$NAPSD_z^{\delta\varphi}(\omega) = C \cdot NAPSD_z^{\delta\alpha}\frac{1}{\left(1+\omega^2\tau_\lambda^2\right)^2}, \tag{3}$$

where $V(z')$ = void velocity at z', ω= angular frequency, $i = \sqrt{-1}$, and

$$\tau_\lambda = \frac{1}{V(z)\lambda(z)}. \tag{4}$$

The break frequency of $NAPSD_z^{\delta\varphi}(\omega)$ is

$$f_b(z) \equiv f_b(\alpha) = \frac{1}{2\pi}V(z)\lambda(z). \tag{5}$$

The numerical Monte Carlo simulations by Dykin and Pázsit (2013) show that the normalized APSD obtained by the Fourier transform of Eq. (1) is represented by the Lorentzian form as described in Eq. (3). Hence, the void profile was successfully reconstructed using the break frequency of the normalized APSD.

The neutron noise is measured by the fluctuation of neutron detector signals that are sensitive to the thermal neutron flux. The fluctuation of the thermal neutron flux due to the void fluctuation is produced by the change in the slow down from the higher neutron energy and the change in the thermal neutron absorption. The propagation of the neutron noise may depend on the diffusion length. The diffusion length changes with the neutron energy. Thus, the thermal neutron noise appears as a synthesis of the neutron noises that propagate differently with their energy. The neutron noise dependence on energy induces a complex APSD dependence on the frequency.

This paper tries to expand the conventional studies on the neutron noise induced by the void fluctuations to multi-group problems and discusses the effect of the energy dependence. The multi-group Monte Carlo method developed by the authors is used for this study. Another objective of this paper is to scrutinize the neutron noise properties in a void-containing water flow using the multi-group neutron noise transport theory.

2. Calculation method for propagating perturbation by the Monte Carlo method

2.1. Transport equation in frequency domain for neutron noise

Although the basic theory of this study is already presented in the previously published literature (Yamamoto, 2013, 2014), it is briefly presented here again. Throughout this study, we consider neutron transport problems within a homogeneous but non-uniform medium of void-containing light water. The void