Progress in Nuclear Energy 101 (2017) 270–278

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Time-dependent Monte Carlo simulations for neutron noise in void-containing water flow

Toshihiro Yamamoto

Research Reactor Institute, Kyoto University, 2 Asashiro Nishi, Kumatori-cho, Sennan-gun, Osaka, 590-0494, Japan

ARTICLE INFO

Article history:
Received 3 December 2016
Received in revised form
7 July 2017
Accepted 29 August 2017

Keywords:
Void
BWR
Neutron noise
Time domain
Monte Carlo

ABSTRACT

Neutron noise measurements for obtaining void-related information of a void-containing water flow are simulated using the time-dependent Monte Carlo technique. In the simulations, circular bubbles move upward in a two-dimensional water channel. The Auto Power Spectral Density (APSD) and the Cross-Correlation Function (CCF) of the neutrons that penetrate the channel are obtained using the time series data of the detected neutrons. If the void velocity is not exceedingly high and the length of neutron detector is not exceedingly short, the APSD shows a characteristic structure where repeated dips and peaks appear in the low frequency region ($f < 100$ Hz). The Monte Carlo simulations reproduce the structure in the APSDs. The void velocity can be roughly estimated using the frequencies of the dips and/or the peaks if the detector length is known. A CCF between two axially displaced detectors presents a prominent peak at the time lag that corresponds to the void transit time. Because the maximum point of the CCF can be clearly identified, the CCF is more favorable than the APSD for the purposes of determining the void velocity. The properties of the APSD and the CCF are discussed for a water channel for which the void velocity varies in the horizontal direction.

1. Introduction

The determination of void-related information (e.g., void transit time (or void velocity) and void fraction) is an important task for safe and reliable operations of boiling water reactors. The void-related information can be determined by the neutron noise measured using in-core neutron detectors, such as the Local Power Range Monitors (LPRMs) and the Traversing In-core Probe (TIP) (Kosály and Meskó, 1976; Kosály, 1980; Kosály et al., 1982; Pázsit and Demazière, 2010; Pázsit and Dykin, 2010; Kiss et al., 2010; Dykin and Pázsit, 2013). A well-known method is the use of an auto power spectral density (APSD) in a single detector or the use of a Cross Correlation Function (CCF) or a Cross Power Spectral Density (CPSD) between axially displaced neutron detector pairs. A nonstochastic approach for void monitoring uses the neutron transmittance that varies depending on the void fraction. Loberg et al. (2010) proposed a method that uses the difference of transmittance between the thermal- and fast-neutron fluxes in void-containing water.

In the conventional approach for neutron noise studies, the neutron noise measured by in-core monitors was reproduced using a simple analytical model that contains unknown parameters (e.g., void velocity and spatial decay constant of neutron noise) (Kosály, 1980; Behringer et al., 1977). Instead of using actually measured noise data, another approach for the development of the diagnostics using the neutron noise technique uses a numerical simulation of the stochastic properties of the random process by random sampling methods. Through these numerical simulations, one can evaluate the possibility and accuracy of the diagnostic technique. A Monte Carle simulation is a very powerful tool for investigating the properties of the technique using neutron noise. To evaluate the performance of the neutron noise techniques for void-related information determination, some studies using the Monte Carlo simulation technique were performed (Pázsit et al., 1984; Dykin and Pázsit, 2013; Yamamoto, 2014; Pettersen et al., 2015; Yamamoto and Sakamoto, 2016).

Two-dimensional circular bubbles that move upward were explicitly allocated at random positions in a water flow channel by (Dykin and Pázsit, 2013). The corresponding neutron noise signals were generated at some elevations of the channel. By processing the neutron noise signals, the break frequencies of the APSDs and the CCFs were obtained to deduce the axial profile of the void

E-mail address: toshihiro.yamamoto223@gmail.com.

http://dx.doi.org/10.1016/j.pnucene.2017.08.013

transit time and the void fraction.

A frequency domain transport equation for neutron noise was solved using a complex-valued weight Monte Carlo method by (Yamamoto and Sakamoto, 2016). By solving the transport equation, a complex-valued neutron noise distribution was obtained for each frequency. Using the Monte Carlo method, the APSD and the CPSD can be calculated based on the transport theory. However, the calculations were performed for water flow whose density was homogeneously reduced according to the void fraction. In other words, the heterogeneity effect in water flow consisting of air bubbles and liquid water (or water droplets and ambient air) was not taken into account in the study. In fact, neutrons fly straight through a voided region without undergoing any collision, whereas they are hindered from moving forward in the water region. The neutron counts increase when many voids exist near a neutron detector. As the number of voids passing near the neutron detector per unit time increases, the neutron noise in the high-frequency region increases. Such a micro-level phenomenon that does not occur in homogenously diluted water may affect the neutron noise signals detected in the in-core monitors.

In the following sections, Monte Carlo simulations are performed in a water flow channel. The time series data of detected neutrons calculated by the Monte Carlo simulations are processed to obtain the APSDs and CCFs. The properties of the APSDs and the CCFs calculated by the Monte Carlo simulations are investigated from the viewpoint of how accurately the void velocity can be predicted using the neutron noise technique. The void velocity in a Boiling Water Reactor (BWR) fuel assembly differs both horizontally and vertically. As Kosály indicated (Kosály, 1980), a neutron detector located between the four fuel assemblies may not see the total assembly areas, and only the inner (close to the detector) parts of the assemblies contribute to the signal of the detector. We are interested in determining what the neutron noise represents if the void velocity or the void fraction varies across the cross-section of the assemblies. The novel aspect of this paper is directly performing time-dependent Monte Carlo simulations for neutron transport phenomena in a water flow where bubbles or droplets are explicitly distributed and move upward in a channel. The objective of this paper is to provide new insight into the void-related information predicted by the neutron noise technique through time-dependent Monte Carlo simulations. In particular, this paper focuses on how effectively noise signal processing can lead to non-uniform flow characterization.

2. Theory of neutron noise

The flux fluctuation of an in-core monitor is composed of the "local component" and the "global component" (Behringer et al., 1977). The "local component" is driven by the fluctuation of the neutron transport properties near the neutron detector, such as the fluctuation of steam-volume. The fluctuation that affects the overall reactivity change of the reactor is referred to as a "global component". This paper focuses on the "local component" only. We consider a line detector of length L that is placed axially. Kosály and Meskó (1976) derived the formula for the APSD of a local component driven by local disturbances:

$$APSD(\omega) \propto H_n(\omega) H_d(\omega), \tag{1}$$

$$H_n(\omega) = \frac{1}{\left(1+\omega^2\tau_n^2\right)^2}, \ \tau_n = \frac{1}{\mu V}, \tag{2}$$

$$H_d(\omega) = \frac{\sin^2(\omega\tau_d)}{(\omega\tau_d)^2}, \ \tau_d = \frac{L}{2V}, \tag{3}$$

where ω = angular frequency, V = axial void velocity, and μ = spatial decay constant of local component. If the detector length is adequately short or the void velocity is sufficiently high, $H_d(\omega)$ can be considered to be constant throughout the frequency range of interest. Then, the APSD is governed by the Lorentz form defined by Eq. (2). The break frequency of Eq. (2), $1/\tau_n$, is related to the void velocity and the void fraction. Otherwise (i.e., the detector length is not so short and the void velocity is not so high), sharp dips of $H_d(\omega)$ that exist at the frequencies $\omega_n = 2n\pi V/L$ ($n = 1, 2, \ldots$) are clearly observed, even in the low-frequency region ($f < 100$ Hz). The frequencies of the dips (or peaks) are determined by the length L and the velocity V. The void velocity can also be determined by the frequencies that maximize the APSD, ω_p. The void velocity is given by the root of the equation below:

$$\omega_p \frac{L}{2V} = \tan\left(\omega_p \frac{L}{2V}\right) \tag{4}$$

Using the frequency of a dip, the void velocity is given by

$$V = \frac{\omega_n L}{2\pi\, n}, \ n = 1, \ 2, \ \ldots, \tag{5}$$

where ω_n = the frequency of the nth dip. Thus, once the detector length is known, the void velocity can be determined by the frequencies of the dips and/or the peaks of the APSD. This paper addresses the situation where the structure of Eq. (3) is dominant in the low-frequency range.

Another method to obtain the void velocity is to use the CCF between two axially aligned detectors. The void transit time is defined as a time for local disturbances caused by moving voids to travel a distance between the midpoints of two detectors. Because the void transit time corresponds to the time lag that maximizes the CCF, the void velocity can be easily determined by the CCF.

3. Monte Carlo calculation method

The Monte Carlo simulations are performed for a two-dimensional rectangular geometry, as shown in Fig. 1. An in-house research-purpose Monte Carlo code developed by the author is used for the simulations. The code has been used for neutron noise analyses and k_{eff}-eigenvalue problems, and it was verified through comparison with the theoretical or other computational methods (e.g., Yamamoto and Sakamoto, 2014; Yamamoto, 2015).

Circular bubbles move upward in the water channel having a width of 5 cm. First, the circular bubbles are distributed at random

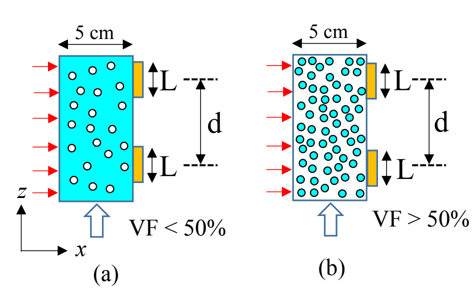

Fig. 1. Schematic view of the water channel ((a) bubbly flow (void fraction (VF) < 50%), (b) dispersed flow (VF > 50%)).