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A new Monte Carlo method for neutron noise calculations in the frequency domain

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ABSTRACT

Neutron noise equations, which are obtained by assuming small perturbations of macroscopic cross sections around a steady-state neutron field and by subsequently taking the Fourier transform in the frequency domain, have been usually solved by analytical techniques or by resorting to diffusion theory. A stochastic approach has been recently proposed in the literature by using particles with complex-valued weights and by applying a weight cancellation technique. We develop a new Monte Carlo algorithm that solves the transport neutron noise equations in the frequency domain. The stochastic method presented here relies on a modified collision operator and does not need any weight cancellation technique. In this paper, both Monte Carlo methods are compared with deterministic methods (diffusion in a slab geometry and transport in a simplified rod model) for several noise frequencies and for isotropic and anisotropic noise sources. Our stochastic method shows better performances in the frequency region of interest and is easier to implement because it relies upon the conventional algorithm for fixed-source problems.

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1. Introduction

Traditional neutron noise analysis addresses the description of time-dependent flux fluctuations induced by small global or local perturbations of the macroscopic cross sections, which may occur in nuclear reactors due to stochastic density fluctuations of the coolant, to vibrations of fuel elements, control rods, or any other structures in the core (Pázsit and Demazière, 2010). Neutron noise techniques are adopted in the nuclear industry for non-invasive general monitoring, control and detection of anomalies in nuclear power plants (Fry et al., 1986). They are also applied to the measurement of the properties of the coolant, such as speed and void fraction (Kosály, 1980). In power reactors, ex-core and in-core detectors can be used to monitor neutron noise with the aim of detecting possible anomalies and taking the necessary measures for continuous safe power production.

The general noise equations are obtained by assuming small perturbations around a steady-state neutron flux and by subsequently taking the Fourier transform in the frequency domain. The analysis is performed based on the neutron kinetic equations, including the coupling with neutron precursors. The outcome of the Fourier transform analysis is a fixed-source equation with complex operators for the perturbed neutron field, which can then be solved so as to predict noise measurements at detector locations. For each frequency, the neutron flux is a complex function having an amplitude and a phase.

Until recently, neutron noise equations have been only solved by analytical techniques (Pázsit and Analytis, 1980; Jonsson et al., 2012) and by resorting to diffusion theory (Demazière, 2011; Malmir et al., 2010). It is therefore necessary to validate these approaches via Monte Carlo simulation. In 2013, a Monte Carlo algorithm was first proposed in order to solve the transport equation in neutron noise theory (Yamamoto, 2013). Such algorithm is a cross-over between fixed-source and power iteration methods and adopts a weight cancellation technique developed by the same author for neutron leakage-corrected calculations or higher order mode eigenvalue calculations (Yamamoto, 2009, 2012a, 2012b). This method yields satisfactory results but has some shortcomings, such as the need of introducing a "binning procedure" for the weight cancellation: each fissile region must be divided into a large number of small regions where positive and negative weights are summed up and cancelled.

In this work, we present a new Monte Carlo method that does not need any weight cancellation technique. This method is inspired by a recent technique developed in Zoia et al. (2014, 2015) for alpha eigenvalue calculations and introduced for reactor

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noise calculations (in concise form) in Rouchon et al. (2016). This paper is organized as follows. In Section 2, the general neutron noise theory will be briefly introduced and the new Monte Carlo method will be presented. Some extensions of the work discussed in Rouchon et al. (2016) will be presented. In Section 3, we will compare our Monte Carlo method and the method proposed in Yamamoto (2013) in the simplified rod model to deterministic methods (slab diffusion and rod transport) for isotropic and anisotropic noise sources, and for frequencies in the range [0.01 Hz, 100 Hz] (which is of interest for applications in reactor physics (Kosály, 1980)) where the conventional algorithm for fixed-source problems can be used for both Monte Carlo methods. In Section 4, we will compare both Monte Carlo methods at low and very high frequencies, and we will analyse the impact of the implicit capture on the algorithms and the convergence rate of the neutron noise equation. Conclusions will be presented in Section 5.

2. Monte Carlo methods for neutron noise theory

2.1. Neutron noise equations

Here we summarize the theory of neutron noise. The reformulation of these equations for diffusion theory is straightforward. Note that the zero power reactor noise (fluctuations inherent to the branching process) is neglected in power reactor noise theory (Pázsit and Demazière, 2010).

We assume small perturbations of the macroscopic cross sections around the following critical steady state:

$$L_0(r,\Omega,E)\Psi_0(r,\Omega,E)=0, \tag{1}$$

where Ψ_0 is the steady-state angular flux and $L_0=\Omega.\nabla+\Sigma_0-H_0-P_0$ the steady-state Boltzmann operator with Σ_0 the steady-state total cross section, H_0 the steady-state scattering operator and P_0 the steady-state production operator. For the steady state, the effective multiplication factor is assumed to be $k=1$. For a system with one precursor group and one fissile isotope, the critical steady-state Boltzmann equation is:

$$\begin{aligned}(\Omega.\nabla+\Sigma_0(r,E))\Psi_0(r,\Omega,E)\\ &=\iint\Sigma_{0,s}(r,\Omega'.\Omega,E'\to E)\Psi_0(r,\Omega',E')dE'd\Omega'\\ &\quad+\frac{1}{k}\frac{\chi(E)}{4\pi}\iint\nu(E')\Sigma_{0,f}(r,E')\Psi_0(r,\Omega',E')dE'd\Omega'.\end{aligned} \tag{2}$$

We impose a temporal perturbation of the cross sections, which yields the kinetic equation:

$$\left[\frac{1}{\mathrm{v}}\partial_t+L(r,\Omega,E,t)\right]\Psi(r,\Omega,E,t)=0, \tag{3}$$

where Ψ is the angular flux, v the neutron velocity and $L=\Omega.\nabla+\Sigma-H-P$ the kinetic Boltzmann operator with Σ the total cross section, H the scattering operator and P the production operator containing prompt and delayed neutron contributions. We impose a periodic perturbation of the kinetic operator with a period T_0, in the form:

$$L(r,\Omega,E,t)=L_0(r,\Omega,E)+\delta L(r,\Omega,E,t). \tag{4}$$

This perturbation is supposed to start at time $t=-\infty$, so that we can reasonably assume that the asymptotic perturbation regime is attained. A similar decomposition is also used for the angular flux:

$$\Psi(r,\Omega,E,t)=\Psi_0(r,\Omega,E)+\delta\Psi(r,\Omega,E,t), \tag{5}$$

where the perturbation term $\delta\Psi$ is called "neutron noise". Finally, plugging expressions (4) and (5) into Eq. (3) leads to a kinetic source equation for the neutron noise:

$$\left[\frac{1}{\mathrm{v}}\partial_t+L(r,\Omega,E,t)\right]\delta\Psi(r,\Omega,E,t)=-\delta L(r,\Omega,E,t)\Psi_0(r,\Omega,E). \tag{6}$$

The second order term $\delta L\delta\Psi$ will be neglected, so that we obtain the traditional linearized kinetic equation:

$$\left[\frac{1}{\mathrm{v}}\partial_t+L_0(r,\Omega,E)\right]\delta\Psi(r,\Omega,E,t)=-\delta L(r,\Omega,E,t)\Psi_0(r,\Omega,E). \tag{7}$$

We want to determine the unique periodic solution of this equation. We apply the Fourier transform and we obtain the noise equation in the usual form:

$$L_{0,\omega}(r,\Omega,E)\delta\Psi(r,\Omega,E,\omega)=-\delta L(r,\Omega,E,\omega)\Psi_0(r,\Omega,E), \tag{8}$$

where $L_{0,\omega}=i\frac{\omega}{\mathrm{v}}+\Omega.\nabla+\Sigma_0-H_0-P_{0,\omega}$ is a modified (complex) Boltzmann operator, i the imaginary unit and $\omega=2\pi f$ the angular frequency. The right hand side of Eq. (8) represents a (known) "noise source". The terms H_0 and $P_{0,\omega}$ are defined by:

$$\begin{aligned}&H_0\delta\Psi(r,\Omega,E,\omega)\\ &\quad=\iint\Sigma_{0,s}(r,\Omega'.\Omega,E'\to E)\delta\Psi(r,\Omega',E',\omega)dE'd\Omega',\\ &P_{0,\omega}\delta\Psi(r,\Omega,E,\omega)\\ &\quad=\frac{1}{k}\frac{\chi_p(E)}{4\pi}\iint\nu_p(E')\Sigma_{0,f}(r,E')\delta\Psi(r,\Omega',E',\omega)dE'd\Omega'\\ &\qquad+\frac{1}{k}\frac{\chi_d(E)}{4\pi}\iint\nu_{d,\omega}(E')\Sigma_{0,f}(r,E')\delta\Psi(r,\Omega',E',\omega)dE'd\Omega'.\end{aligned} \tag{9}$$

For a system with one precursor group and one fissile isotope, the noise equation therefore reads:

$$\begin{aligned}&\left(\Omega.\nabla+\Sigma_0(r,E)+i\frac{\omega}{\mathrm{v}}\right)\delta\Psi(r,\Omega,E,\omega)\\ &\quad=\iint\Sigma_{0,s}(r,\Omega'.\Omega,E'\to E)\delta\Psi(r,\Omega',E',\omega)dE'd\Omega'\\ &\qquad+\frac{1}{k}\frac{\chi_p(E)}{4\pi}\iint\nu_p(E')\Sigma_{0,f}(r,E')\delta\Psi(r,\Omega',E',\omega)dE'd\Omega'\\ &\qquad+\frac{1}{k}\frac{\chi_d(E)}{4\pi}\iint\nu_{d,\omega}(E')\Sigma_{0,f}(r,E')\delta\Psi(r,\Omega',E',\omega)dE'd\Omega'\\ &\qquad+S(r,\Omega,E,\omega),\end{aligned} \tag{10}$$

where $\nu_{d,\omega}(E)=\left(\frac{\lambda^2}{\lambda^2+\omega^2}-i\frac{\lambda\omega}{\lambda^2+\omega^2}\right)\nu_d(E)$. All other notations are standard. The noise source S is defined by:

$$\begin{aligned}&S(r,\Omega,E,\omega)=-\delta\Sigma(r,E,\omega)\Psi_0(r,\Omega,E)\\ &\quad+\iint\delta\Sigma_s(r,\Omega'.\Omega,E'\to E,\omega)\Psi_0(r,\Omega',E')dE'd\Omega'\\ &\quad+\frac{1}{k}\frac{\chi_p(E)}{4\pi}\iint\nu_p(E')\delta\Sigma_f(r,E',\omega)\Psi_0(r,\Omega',E')dE'd\Omega'\\ &\quad+\frac{1}{k}\frac{\chi_d(E)}{4\pi}\iint\nu_{d,\omega}(E')\delta\Sigma_f(r,E',\omega)\Psi_0(r,\Omega',E')dE'd\Omega',\end{aligned} \tag{11}$$

where $\delta\Sigma_x(r,E,\omega)$ is the Fourier transform of the perturbed term of the macroscopic cross section $\Sigma_x(r,E,t)=\Sigma_{0,x}(r,E)+\delta\Sigma_x(r,E,t)$. Observe that in Yamamoto (2013), it is assumed that the total cross section is the only time-dependent cross section.

Thus, because of the delayed neutrons, the production operator $P_{0,\omega}$ depends on the frequency. Eq. (10) can be conceptually split into a system of two equations for the real and imaginary part of $\delta\Psi$. The two equations are formally coupled by two terms: $i\frac{\omega}{\mathrm{v}}$ and the modified production operator $P_{0,\omega}$.

2.2. A new Monte Carlo method for the noise equations

A stochastic method has been first provided in Yamamoto (2013) to solve the fixed-source problem described by Eq. (10). This method is based on the simulation of particles carrying com-

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