Annals of Nuclear Energy 114 (2018) 482–494

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Neutron noise simulation in the nuclear reactor core based on the average current nodal expansion method

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ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form 12 August 2017
Accepted 14 August 2017

Keywords:
Neutron noise calculation
Frequency domain
Average current nodal expansion method
Adjoint solution

ABSTRACT

In this work, the zeroth order of average current nodal expansion method (ACNEM) is developed for the neutron noise simulation of nuclear reactors core with two dimensional rectangular fuel assemblies. At first, the static calculation is performed for the forward treatment of diffusion equation. Then the forward neutron noise is earned by solving the diffusion equation in the frequency domain using the zeroth order of ACNEM. For the neutron noise calculation in the domain of reactor core, the noise source is considered as an "absorber with variable strength" type *i.e.* the absorption cross section can be changed in the selected material. In order to evaluate the accuracy of exploited scheme, the neutron noise simulation is performed for two well-known test cases including 2-D LRA BWR and 2-D BIBLIS PWR. For benchmarking purpose, the adjoint noise calculation is done for comparing results with the forward approach using a conventional relation in an elected non-zero frequency. Also the contrast of results is illustrated between the neutron noise in the zero frequency and the corresponding earned static fluxes. Totally, numerical results of problems validate the accuracy of the neutron noise simulation using the proposed method.

1. Introduction

The neutron noise is the time-fluctuations of the neutron flux around its steady-state value that are due to the cases such as displacement of core component, temperature or density changes and etc. Noise analysis method has many different applications in reactor noise diagnostics and it can be used for determining the dynamic parameters such as decay ratio in BWRs and Moderator Temperature Coefficient (MTC) in PWRs, Demaziere and Pazsit (2008). One of the important advantages of the neutron noise measurement is that the noise can be achieved without interrupting the operation of the reactor, Pazsit and Demaziere (2010).

Multiple efforts have been performed for developing suitable methods of neutron noise calculations via the reactor transfer function. A 2-D 2-group neutron noise simulator was developed which calculates the direct and corresponding adjoint transfer function in the frequency domain. The spatial discretization is based on the finite difference method for the rectangular geometries, Demaziere (2004). A noise simulator was also reported which calculates both the forward and adjoint neutron noises by the finite difference method, Malmir et al. (2010). Also the calculation of 2-group neutron noise was performed using the Analytical Nodal Method (ANM) for the spatial discretization of neutron diffusion equation, Larsson et al. (2011). In addition, using one/two-group diffusion theory, the neutron noise analysis was done by considering a noise source which includes the fluctuations of the fission cross sections and the fluid velocity, Dykin et al. (2016). Moreover, a new Monte Carlo method was developed for neutron noise calculations by solving the transport neutron noise equations in the frequency domain, Rouchon et al. (2017). Recently, the neutron noise simulation using the zeroth order of point flux nodal expansion method (AFNEM) was also reported, Abed et al. (2017). In this work, both forward and adjoint neutron noises were calculated and verified for some popular test cases.

The Nodal Expansion Method (NEM) is an approach which can be used for the spatial discretization. This method originated from the Nodal Synthesis Method by eliminating the fine-mesh calculations and improving the calculation of inter-node coupling coefficients. For large multi-dimensional realistic problems, nodal methods can be considered with elements as large as fuel assemblies, Poursalehi et al. (2012). Average current nodal expansion method (ACNEM) is one of NEM schemes which has been newly developed for the calculation of static, multi-group and three-dimensional diffusion equation using an adopted innovative iterative approach, Poursalehi et al. (2012, 2013).

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https://doi.org/10.1016/j.anucene.2017.08.024
0306-4549/

In this research, the neutron noise analysis is performed based on the zeroth order of average current nodal expansion method (ACNEM) by implementing the aforementioned iterative scheme, Poursalehi et al. (2012, 2013), which has been proposed and used for the steady state calculations earlier. First, the zeroth order of ACNEM is described briefly for the solution of static neutron diffusion equation in both forward and adjoint treatments. Afterward, the neutron noise calculation strategy using zeroth order of ACNEM is given along with the corresponding derived equations in the frequency domain for both forward and adjoint approaches. Two well-known methods which have been usually used in validating of neutron noise calculations are applied for two test cases including BIBLIS PWR and LRA BWR. At last, numerical results of noise analysis for these problems are presented. In this regard, one can realize the sufficient accuracy and the successful performance of neutron noise simulation using ACNEM.

2. Static solution based on the zeroth order of average current nodal expansion method

2.1. Calculation of forward flux

In this sub-section, the general aspect of zeroth order ACNEM is given for the static forward calculation of neutron balance equation. For more details, the interested reader is referred to Poursalehi et al. (2012, 2013). The 2D multi group neutron continuity equation integrated over each node Π^{m} is represented by the following equation:

$$\sum_{\substack{u=x,y\\ s=l,r}} \frac{1}{h_u^m}\left\{j_{gus}^{+m}-j_{gus}^{-m}\right\}+\Sigma_{rg}^{m}\Phi_g^{m} = \sum_{\substack{g'=1\\ g'\neq g}}^{G}\Sigma_{gg'}^{m}\Phi_{g'}^{m}+\frac{\chi_g}{k_{eff}}\sum_{g'=1}^{G}\upsilon\Sigma_{fg'}^{m}\Phi_{g'}^{m} \quad (1)$$

$$m=1,2,\cdots,M,\quad g=1,2,\cdots,G,\quad u=x,y$$

where Φ_g^m is the average flux within the node Π^m for group g, $j_{gus}^{+m}, j_{gus}^{-m}$ are the average outgoing (+) and incoming (−) partial currents for group g at the surface of Γ_{us}^{m}, respectively and also h_u^m is the thickness of node Π^m in the u direction.

In the zeroth order of NEM, the neutron flux distribution for any node and energy group is approximated by a second degree polynomial expansion. In this approach, unknown coefficients of the corresponding expansion are calculated in regard of defined principle parameters including the average flux within the node and the average flux across any surface of the node.

For calculating the aforementioned variables, we need define additional equations in that the number of unknown coefficients is equaled to the equations number. Thus, we use the following equation *i.e.* the fick's law in order to relate the average flux within the node to the average surface current in two surfaces located in any Cartesian direction (u = x or y) for two-dimensional scheme:

$$j_{gus}^{+m}-j_{gus}^{-m} = -\frac{1}{A_{us}^{m}}\int_{\Gamma_{us}^{m}} D_g\nabla\phi_g e_{us}^{m}d\Gamma_{us}^{m} = \frac{D_g^m}{h_u^m}\left(-2\Psi_{gus'}^{m}-4\Psi_{gus}^{m}+6\Phi_g^m\right)\quad ,(s'=l,r,s'\neq s) \quad (2)$$

In Eq. (2), Ψ_{gus}^{m} is the average flux for group g at surface Γ_{us}^{m}, ϕ_g is the considered flux expansion for group g and A' is the area of surface Γ_{us}^{m}. Also the average surface flux in the Eq. (2), Ψ_{gus}^{m} , can be defined as respect to corresponding average partial currents in the surface Γ_{us}^{m}, *i.e.*:

$$\Psi_{gus}^{m} = 2\left(j_{gus}^{+m}+j_{gus}^{-m}\right) \quad (3)$$

By this assumption, the surface average fluxes in the Eq. (2) can be omitted; as a result, the Eq. (4) is obtained by involving the average flux within the node and the average surface partial currents as shown by the following relationship:

$$\begin{bmatrix} j_{gul}^{+m}\\ j_{gur}^{+m}\end{bmatrix} = \begin{bmatrix} A_{gu}^{m} & B_{gu}^{m} & C_{gu}^{m}\\ A_{gu}^{m} & C_{gu}^{m} & B_{gu}^{m}\end{bmatrix}\begin{bmatrix}\Phi_g^m\\ j_{gul}^{-m}\\ j_{gur}^{-m}\end{bmatrix} \quad (4)$$

$$m=1,2,\ldots,M,\quad g=1,2,\ldots,G,\quad u=x,y$$

It should be noted that A_{gu}^{m} ,B_{gu}^{m} and C_{gu}^{m} in the Eq. (4) are defined as for D_g^m and h_u^m of the corresponding node.

Now, by removing outgoing currents from the Eq. (1) using Eq. (4), the nodal balance equation is earned with the following form:

$$\left[\sum_{u=x,y}2\frac{A_{gu}^{m}}{h_u^m}+\Sigma_{rg}^{m}\right]\Phi_g^m = \sum_{\substack{g'=1\\ g'\neq g}}^{G}\Sigma_{gg'}^{m}\Phi_{g'}^{m}+\frac{\chi_g}{k_{eff}}\sum_{g'=1}^{G}\upsilon\Sigma_{fg'}^{m}\Phi_{g'}^{m} + \sum_{\substack{u=x,y\\ s=l,r}}\frac{1}{h_u^m}\left(1-B_{gu}^{m}-C_{gu}^{m}\right)j_{gus}^{-m} \quad (5)$$

m = 1,2,. . ., M, g = 1,2,. . ., G, u = x,y

At last, the Eq. (5) for two-dimensional and two energy groups scheme can be indicated in the below matrix form in order to use in subsequent sub-sections.

$$\begin{bmatrix}\frac{2A_{1x}^{m}}{h_x^m}+\frac{2A_{1y}^{m}}{h_y^m}+\Sigma_{R,1,0}^{m} & 0\\ -\Sigma_{s,1\to2,0}^{m} & \frac{2A_{2x}^{m}}{h_x^m}+\frac{2A_{2y}^{m}}{h_y^m}+\Sigma_{a,2,0}^{m}\end{bmatrix}\times\begin{bmatrix}\Phi_{1,0}^{m}\\ \Phi_{2,0}^{m}\end{bmatrix} = \frac{1}{k_{eff}}\begin{bmatrix}\upsilon\Sigma_{f1,0}^{m} & \upsilon\Sigma_{f2,0}^{m}\\ 0 & 0\end{bmatrix}\times\begin{bmatrix}\Phi_{1,0}^{m}\\ \Phi_{2,0}^{m}\end{bmatrix} + \begin{bmatrix}\frac{1}{h_x^m}(1-B_{1x}^{m}-C_{1x}^{m}) & 0\\ 0 & \frac{1}{h_x^m}(1-B_{2x}^{m}-C_{2x}^{m})\end{bmatrix}\times\begin{bmatrix}j_{1xr,0}^{-m}+j_{1xl,0}^{-m}\\ j_{2xr,0}^{-m}+j_{2xl,0}^{-m}\end{bmatrix} + \begin{bmatrix}\frac{1}{h_y^m}(1-B_{1y}^{m}-C_{1y}^{m}) & 0\\ 0 & \frac{1}{h_y^m}(1-B_{2y}^{m}-C_{2y}^{m})\end{bmatrix}\times\begin{bmatrix}j_{1yr,0}^{-m}+j_{1yl,0}^{-m}\\ j_{2yr,0}^{-m}+j_{2yl,0}^{-m}\end{bmatrix} \quad (6)$$

In the Eq. (6), subscripts 0, 1 and 2 refer to the static situation, the fast and thermal energy groups, respectively. But an additional set of equations for solving the Eq. (6) is required for estimating the incoming current in any surface of the node. For internal surfaces, the incoming current in each surface can be achieved using the corresponding outgoing current of the adjacent node obtained by Eq. (4). In addition, for exterior surfaces in the domain, boundary conditions can be applied. However, these steps of calculation have been included in an adopted iterative approach and presented in the earlier published paper, Poursalehi et al. (2013).

2.2. Calculation of adjoint flux

In this subsection, the calculation of adjoint function using ACNEM is reported briefly for the zeroth order of solution. In static calculations, the estimated multiplication factor by forward and adjoint approaches are equal and for two group diffusion theory, the adjoint operator is the transpose of forward operator, Bell and Glasstone (1970).

The general form of diffusion equation in the operator notation can be written by:

$$M\Phi = \frac{1}{k_{eff}}F\Phi \quad (7)$$