Annals of Nuclear Energy 62 (2013) 158–169

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

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

A multi-group neutron noise simulator for fast reactors

Hoai Nam Tran [a,*], Florian Zylbersztejn [a,b], Christophe Demazière [a], Christian Jammes [b], Philippe Filliatre [b]

[a] Chalmers University of Technology, Department of Applied Physics, Division of Nuclear Engineering, SE-412 96 Gothenburg, Sweden
[b] Commissariat à l'énergie atomique et aux énergies alternatives (CEA), DEN, Cadarache, DER/SPEx/LDCI, F-13108 Saint-Paul-lez-Durance, France

ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form 12 June 2013
Accepted 12 June 2013

Keywords:
Neutron noise
Fast reactor
Hexagonal geometry
ESFR

ABSTRACT

A neutron noise simulator has been developed for fast reactors based on diffusion theory with multi-energy groups and several groups of delayed neutron precursors. The tool is expected to be applicable for core monitoring of fast reactors and also for other reactor types with hexagonal fuel assemblies. The noise sources are modeled through small stationary fluctuations of macroscopic cross sections, and the induced first order noise is solved fully in the frequency domain. Numerical algorithms are implemented for solving both the static and noise equations using finite differences for spatial discretization, where a hexagonal assembly is radially divided into finer triangular meshes. A coarse mesh finite difference (CMFD) acceleration has been used for accelerating the convergence of both the static and noise calculations. Numerical calculations have been performed for the ESFR core with 33 energy groups and 8 groups of delayed neutron precursors using the cross section data generated by the ERANOS code. The results of the static state have been compared with those obtained using ERANOS. The results show an adequate agreement between the two calculations. Noise calculations for the ESFR core have also been performed and demonstrated with an assumption of the perturbation of the absorption cross section located at the central fuel ring.

1. Introduction

Neutron noise analysis has been early considered as a powerful technique in reactor diagnostics and core monitoring (Thie, 1981; Pázsit and Demazière, 2010). Online reactor diagnostics for monitoring the operating status of LWRs based on analyzing the measured noise signals were deployed widely in various countries (Umeda et al., 1988; Grondey et al., 1985; Wach, 1991; Bastl et al., 1985; Hashemian, 2011).

The numerical simulation of the neutron noise still remains a challenge for describing detector signals and improving core surveillance. Recently, several attempts have been carried out for the development of numerical simulations of the space- and frequency-dependent neutron noise for LWRs based on two-group diffusion theory, such as the CORE SIM code using a finite difference method in Cartesian geometries (Demazière, 2004, 2011; Demazière and Pázsit, 2009), an analytical nodal method (Larsson et al., 2011), and hexagonal geometries (Malmir et al., 2010; Hosseini and Vosoughi, 2012; Tran and Demazière, 2012). The neutron noise is solved in the frequency domain, while the noise source is modeled via the fluctuations of macroscopic cross sections. Various types of the noise, e.g. perturbations of cross sections and/or vibrating absorber or fuel assemblies, can be simulated through defining the fluctuations of cross sections as input parameters. A number of applications have been investigated for LWRs (Demazière and Pázsit, 2009).

Previous investigations show that the noise in the fast group could provide useful information for identifying vibrations induced by absorber or fuel rods in the core of LWRs (Jonsson et al., 2012). It is also believed that the noise measured by ex-core detectors in a sodium-cooled fast reactor (SFR) could be useful for assessing the dynamic condition of the core (Thie, 1988; Tamaoki and Takahashi, 1992). Measurement of the neutron noise in fast reactors and a test facility has also been done (Gourdon and Casejuane, 1982; Thie, 1988; Le Guillou et al., 1977). Therefore, it is highly desirable to extend the noise calculation method to fast reactors which usually have hexagonal fuel assemblies.

The development of a new noise simulator for fast reactors was also motivated by the needs to support the safety in design and operation of future SFRs. The French Commissariat à l'énergie atomique et aux énergies alternatives (CEA) and Sweden are presently collaborating on research activities in support to the SFR safety. The tool is expected to give a possibility to investigate the noise behavior in the SFR cores and support the development of the neutron instrumentation for the fast reactors, which will mainly rely on the high temperature fission chambers specifically developed for being placed in the reactor tank (Filliatre et al., 2010; Jammes et al., 2010, 2012).

This paper presents the numerical development of a neutron noise simulator for fast reactors with hexagonal fuel assemblies. The numerical implementation was based on diffusion theory with

* Corresponding author. Tel.: +46 31 772 3152; fax: +46 31 772 3079.
E-mail address: nam@nephy.chalmers.se (H.N. Tran).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.06.017

multi-energy groups for solving both the static and noise equations, where the neutron noise equation was solved fully in the frequency-domain with several groups of delayed neutron precursors. A finite difference method was used for spatial discretization, where a prismatic hexagonal assembly is radially divided into finer triangular meshes. A coarse-mesh finite difference (CMFD) acceleration was employed for accelerating the convergence of both the static and noise calculations, in which a coarse mesh is radially defined as a hexagonal assembly.

Numerical calculation and verification have been performed for a large SFR core, which has been studied within the European Sodium Fast Reactor Collaborative Project (CP-ESFR project) in the 7th framework program (FP7) with the involvement of 25 European partners and French CEA (named ESFR core). The calculation model was based on 33 energy groups and 8 groups of delayed neutron precursors. In this paper, the static calculations have been performed and benchmarked against ERANOS. For this purpose, the cross sections of the ESFR core have been generated from ERANOS for the use in this simulator. Since reference calculations of the neutron noise have not been so far available for more than two-energy groups, there is no available reference for benchmarking the frequency-dependent noise in a multi-group model. However, the noise calculations could still be considered as reliable if the static calculations give adequate accuracy. In the present paper, calculations of the space- and frequency-dependent noise induced by the perturbation of the absorption cross section near the core center have been performed and discussed.

2. Multi-group theory and numerical solution method for fast reactors

2.1. Static and noise equations

In order to solve the neutron noise equation, it is necessary to define a noise source which is usually modeled through the fluctuations of static cross sections. For the noise source definition, it is necessary to know the static state of the system such as the k_{eff} and the static fluxes. This means that the solution of the static equation is also required. Thus, in this simulator, the numerical implementation is for solving both the static and noise equations. The multi-group diffusion equation for the static state is written as follows:

$$-\nabla\cdot[D_g\nabla\phi_g(\mathbf{r})]+\Sigma_{t,g}\phi_g(\mathbf{r})=\frac{1}{k_{eff}}\chi_g\sum_{g'}\nu\Sigma_{f,g'}\phi_{g'}(\mathbf{r})+\sum_{g'\neq g}\Sigma_{s,g'\to g}\phi_{g'}(\mathbf{r}) \tag{1}$$

where $g = 1, 2, \ldots, G$ denotes the energy group, ϕ_g is the neutron flux in group g, D_g is the diffusion coefficient in group g, $\nu\Sigma_{f,g}$ is the production cross section in group g, $\Sigma_{s,g'\to g}$ is the scattering cross section from group g' to group g, and $\Sigma_{t,g}$ is the total cross section, which is defined as

$$\Sigma_{t,g}=\Sigma_{a,g}+\sum_{g'\neq g}\Sigma_{s,g\to g'}, \tag{2}$$

$\Sigma_{a,g}$ is the absorption cross section in group g, χ_g is the fission energy spectrum, which is expressed via the prompt, χ_g^p and delayed, $\chi_{g,j}^d$ spectra as follows:

$$\chi_g=(1-\beta)\chi_g^p+\sum_j\beta_j\chi_{g,j}^d. \tag{3}$$

Further, $j = 1, 2, \ldots, J$ denotes the group of delayed neutron precursors, and β is the total fraction of delayed neutrons

$$\beta=\sum_j\beta_j. \tag{4}$$

All cross sections in Eqs. (1) and (2) are space-dependent but for the sake of brevity, the space-dependence is dropped.

The multi-group noise equation is obtained from the space- and time-dependent diffusion equations by assuming that all time-dependent terms, $X(\mathbf{r},t)$, can be split into a stationary component, $X_0(\mathbf{r})$, which corresponds to the value at the steady state, plus a small fluctuation, $\delta X(\mathbf{r},t)$ as

$$X(\mathbf{r},t)=X_0(\mathbf{r})+\delta X(\mathbf{r},t). \tag{5}$$

By assuming that the fluctuations are small so that only the first order noise needs to be taken into account, products of fluctuating terms can be neglected and the result is a linear equation for the fluctuation of the flux. Subtracting the static equation and after performing a Fourier transform of all time-dependent terms, $\delta X(\mathbf{r},t)$, as

$$\delta X(\mathbf{r},\omega)=\int_{-\infty}^{\infty}\delta X(\mathbf{r},t)e^{-i\omega t}dt, \tag{6}$$

with the assumption that the system was in the unperturbed (critical) state at $t = -\infty$, the first order space- and frequency-dependent neutron noise in multi-group diffusion theory is written as follows

$$\begin{aligned}-\nabla\cdot[D_g\nabla\delta\phi_g(\mathbf{r},\omega)]+\Sigma_{t,g}(\omega)\delta\phi_g(\mathbf{r},\omega)\\=\frac{1}{k_{eff}}\chi_g(\omega)\sum_{g'}\nu\Sigma_{f,g'}\delta\phi_{g'}(\mathbf{r},\omega)+\sum_{g'\neq g}\Sigma_{s,g'\to g}\delta\phi_{g'}(\mathbf{r},\omega)\\+S_g(\mathbf{r},\omega),\end{aligned} \tag{7}$$

where $\delta\phi_g(\mathbf{r},\omega)$ denotes the space- and frequency-dependent noise in group g. The frequency-dependent total cross section in Eq. (7) is written as

$$\Sigma_{t,g}(\omega)=\Sigma_{a,g}(\omega)+\sum_{g'\neq g}\Sigma_{s,g\to g'}, \tag{8}$$

with

$$\Sigma_{a,g}(\omega)=\Sigma_{a,g}+\frac{i\omega}{\upsilon_g}. \tag{9}$$

The k_{eff} in the noise equation is the eigenvalue obtained from the static calculation. $\chi_g(\omega)$ denotes the frequency-dependent fission energy spectrum, which is obtained from the equation of delayed neutron as

$$\chi_g(\omega)=\chi_g-\sum_j\chi_{g,j}^d\frac{i\omega\beta_j}{\lambda_j+i\omega}. \tag{10}$$

The last term on the r.h.s of Eq. (7) is the noise source, which is calculated from the fluctuations of macroscopic cross sections as

$$\begin{aligned}S_g(\mathbf{r},\omega)=-\delta\Sigma_{a,g}(\omega)\phi_g(\mathbf{r})-\sum_{g'\neq g}\delta\Sigma_{s,g\to g'}(\omega)\phi_g(\mathbf{r})\\+\sum_{g'\neq g}\delta\Sigma_{s,g'\to g}(\omega)\phi_{g'}(\mathbf{r})\\+\frac{1}{k_{eff}}\chi_g(\omega)\sum_{g'}\delta\left[\nu\Sigma_{f,g'}(\omega)\right]\phi_{g'}(\mathbf{r}).\end{aligned} \tag{11}$$

In this model, the fluctuation of the diffusion coefficient is neglected. The effect of the fluctuation of the diffusion coefficient on the space-dependent noise will be investigated in a separate work. The static Eq. (1) is an eigenvalue problem, where the k_{eff} and the static fluxes correspond to the fundamental mode, while the balance equation for the neutron noise, as given by Eq. (7), is an inhomogeneous equation with an external source. Another important difference is that all quantities in Eq. (7) are frequency-dependent, i.e. complex quantities.