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On a various noise source reconstruction algorithms in VVER-1000 reactor core

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HIGHLIGHTS

- A sensitivity analysis of unfolding methods to different parameters is done.
- ISM is proposed to reconstruct the noise source of type vibrating absorber.
- Four algorithms are used to solve the system of equations in the inversion method.
- The neutron noise due to a new defined noise source (ILFAIP) is calculated.
- We find that the scanning method is a reliable algorithm for source reconstruction.

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ABSTRACT

In present study, the neutron noise source is reconstructed using three different unfolding techniques in a typical VVER-1000 reactor core. In first stage, the neutron noise calculation based on Galerkin finite element method (GFEM) is performed; in which the neutron noise in two energy group due to the noise sources of type absorber of variable strength and vibrating absorber is calculated. The neutron noise due to inadvertent loading of a fuel assembly in an improper position (ILFAIP), as a new defined noise source in the neutron noise studies, is calculated as well. In the second stage, the inversion, zoning and scanning methods are applied for reconstruction of the noise source of type absorber of variable strength. Also, improved scanning method (ISM) is used to reconstruct the noise source of type vibrating absorber. To solve the system of equations in the inversion method, four different algorithms are used. The obtained results from various unfolding methods are then compared. Finally, a sensitivity analysis of mentioned methods to different parameters like the location of noise source in the reactor core, number of available detectors and fuel burn up is performed.

1. Introduction

Diagnostics of neutron noise source like the control rod vibrations via neutron noise methods have been the subject of a number of prior studies and experiments (Pázsit and Glockler, 1983).

Various unfolding techniques like the inversion, zoning and scanning methods as well as Artificial Neural Networks (ANNs) might be applied to identify and localize the noise sources such as the unseated fuel assemblies, absorber of variable strength or vibrations of core internals in PWRs (Demazière and Andhil, 2005; Williams, 1974; Garis et al., 1998). Similar techniques are applied for identification of the local density wave oscillations in a BWR core (Tambouratzis and Antonopoulos-Domis, 1999). Several researchers tried to develop convenient methods for identification of noise source in the reactor core as given in the following:

1 Pázsit and Glockler (1983, 1984) investigated the possibility of rod vibration diagnostic based on the theory of neutron noise arising from the vibration of a localized absorber in a PWR core. It is found that noise source characteristics, namely rod position, vibration trajectory and spectra can be unfolded from the measured neutron noise signals and proposed numerical method.
2 Garis et al. (1998) localized the control rod vibrations in a PWR core by measuring and spatial unfolding of the induced neutron noise. The method used in this work was based on ANNs.
3 Tambouratzis and Antonopoulos-Domis (2002) proposed the unfolding method based on ANNs for instability localization. The instability was modeled by a variable strength absorber in a two-dimensional bare reactor model with one neutron energy group.
4 Demazière and Andhil (2005) investigated three unfolding methods including inversion, zoning and scanning applied for identification and localization of absorber of variable strength in

Abbreviations: FEM, Finite Element Method; $\delta\phi(r,\omega)$, neutron noise; $\delta\phi^{\dagger}(r,\omega)$, adjoint noise; D_g, diffusion constant in energy group g; ∇, the nabla operator; BOC, begin of cycle; MOC, middle of cycle; EOC, end of cycle.

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the PWR core. The spatial discretization of equations was based on Finite Difference Method (FDM).

In the present study in parallel with aforementioned studies, the neutron noise source of type absorber of variable strength is reconstructed using the inversion, zoning, and scanning methods. Four various algorithms are used to solve the system of equations in the inversion method. As one of the main innovations of the present study, the noise source of type vibrating absorber is reconstructed using proposed Improved Scanning Method (ISM). As another innovation of the present work, the neutron noise due to Inadvertent Loading of a Fuel Assembly in an Improper Position (ILFAIP) is calculated. The reconstruction of two coincidence noise sources of type absorber of variable strength is also the other novelty of this work. To all above mentioned noise simulations and reconstruction processes, Galerkin Finite Element Method (GFEM), a weighted residual method, was used as the static simulator (STA-FEMG) (Hosseini and Vosoughi, 2013) and dynamic simulator (DYN-FEMG) (Hosseini and Vosoughi, 2012). Since there is no experimental data, the obtained neutron noise from DYN-FEMG in the location of detectors is used for noise source reconstruction.

An outline of the remainder of present paper is as follows: In Section 2, we briefly introduces the mathematical formulation used to develop DYN-FEMG. Section 3 presents the main specification of the typical VVER-1000. The results of the neutron noise calculations are given in Section 4. In Section 5, the methods applied for noise source unfolding are described. A sensitivity analysis of various unfolding methods to the location of noise source, number of available detectors as well as the fuel burnup is performed in next section. In Section 7, the results and the accuracy of proposed unfolding methods are discussed. Finally, Section 8 gives the concluding remarks.

2. Noise calculations

2.1. Forward noise calculations

Here, the first-order neutron noise approximation of two-group neutron diffusion equation is applied for noise calculations. Global form of this equation in which the neutron noise sources is due to the variations of scattering, absorption and fission macroscopic cross sections, is given in Eq. (1) (Demazière, 2004):

$$\left[\nabla\cdot\bar{\bar{D}}(\bar{r})\nabla+\bar{\bar{\Sigma}}_{\mathrm{dyn}}(\bar{r},\omega)\right]\times\begin{bmatrix}\delta\phi_1(\bar{r},\omega)\\ \delta\phi_2(\bar{r},\omega)\end{bmatrix}=\bar{\phi}_{s,1\to2}(\bar{r})\delta\Sigma_{s,1\to2}(\bar{r},\omega)+\bar{\bar{\phi}}_a(\bar{r})\begin{bmatrix}\delta\Sigma_{a,1}(\bar{r},\omega)\\ \delta\Sigma_{a,2}(\bar{r},\omega)\end{bmatrix}+\bar{\bar{\phi}}_f(\bar{r},\omega)\begin{bmatrix}\delta\nu_1\Sigma_{f,1}(\bar{r},\omega)\\ \delta\nu_2\Sigma_{f,2}(\bar{r},\omega)\end{bmatrix},\quad(1)$$

where all quantities are defined as usual and the matrices and vectors are expressed as Eqs. (2)–(5):

$$\bar{\bar{\Sigma}}_{\mathrm{dyn}}(\bar{r},\omega)=\begin{bmatrix}-\Sigma_1(\bar{r},\omega) & \dfrac{\nu_2\Sigma_{f,2}(\bar{r})}{k_{\mathrm{eff}}}\left(1-\dfrac{i\omega\beta_{\mathrm{eff}}}{i\omega+\lambda}\right)\\ \Sigma_{s,1\to2}(\bar{r}) & -\left(\Sigma_{a,2}(\bar{r})+\dfrac{i\omega}{\nu_2}\right)\end{bmatrix},\quad(2)$$

$$\bar{\phi}_{s,1\to2}(\bar{r})=\begin{bmatrix}\phi_1(\bar{r})\\ -\phi_1(\bar{r})\end{bmatrix},\quad(3)$$

$$\bar{\bar{\phi}}_a(\bar{r})=\begin{bmatrix}\phi_1(\bar{r}) & 0\\ 0 & \phi_2(\bar{r})\end{bmatrix}\quad(4)$$

$$\bar{\bar{\phi}}_f(\bar{r},\omega)=\begin{bmatrix}-\phi_1(\bar{r})\left(1-\dfrac{i\omega\beta_{\mathrm{eff}}}{i\omega+\lambda}\right) & -\phi_2(\bar{r})\left(1-\dfrac{i\omega\beta_{\mathrm{eff}}}{i\omega+\lambda}\right)\\ 0 & 0\end{bmatrix}\quad(5)$$

The coefficient $\Sigma_1(\bar{r},\omega)$ applied in Eq. (2) is defined as Eq. (6):

$$\Sigma_1(\bar{r},\omega)=\Sigma_{r,1}(\bar{r})+\frac{i\omega}{\nu_1}-\frac{\nu_1\Sigma_{f,1}(\bar{r})}{k_{\mathrm{eff}}}\left(1-\frac{i\omega\beta_{\mathrm{eff}}}{i\omega+\lambda}\right).\quad(6)$$

As shown in Eqs. (3)–(5), the static neutron flux is required for calculating the neutron noise. To this end, two-group, two-dimensional neutron diffusion equation is solved using GFEM. The solution of the equation using GFEM was completely explained in recently published work (Hosseini and Vosoughi, 2013).

In this study, the neutron noise source is considered to be an absorber of variable strength or the vibrating absorber type. To solve the neutron noise equation (Eq. (1)), the Green's function technique is applied (Demazière, 2004). In this method, the Green's function components (neutron noise due to unit neutron noise source) are calculated from Eq. (7):

$$\left[\nabla\cdot\bar{\bar{D}}(\bar{r})\nabla+\bar{\bar{\Sigma}}_{\mathrm{dyn}}(\bar{r},\omega)\right]\times\begin{bmatrix}G_{g\to1}(\bar{r},\overline{r'},\omega)\\ G_{g\to2}(\bar{r},\overline{r'},\omega)\end{bmatrix}=\begin{bmatrix}\delta(\bar{r}-\overline{r'})\\ 0\end{bmatrix}_{g=1}r\begin{bmatrix}0\\ \delta(\bar{r}-\overline{r'})\end{bmatrix}_{g=2},\quad(7)$$

in which, $G_{g\to1}(\bar{r},\overline{r'},\omega)$ and $G_{g\to2}(\bar{r},\overline{r'},\omega)$ are the Green's function components in groups 1 and 2 due to neutron noise source in group g, respectively. The neutron noise source may be considered to be in fast or thermal energy group. The general form of neutron noise source is expressed as Eq. (8):

$$S(\overline{r'},\omega)=\begin{bmatrix}S_1(\overline{r'},\omega)\\ S_2(\overline{r'},\omega)\end{bmatrix}=\bar{\phi}_{s,1\to2}(\overline{r'})\delta\Sigma_{s,1\to2}(\overline{r'},\omega)+\bar{\bar{\phi}}_a(\bar{r})\begin{bmatrix}\delta\Sigma_{a,1}(\overline{r'},\omega)\\ \delta\Sigma_{a,2}(\overline{r'},\omega)\end{bmatrix}+\bar{\bar{\phi}}_f(\overline{r'}\omega)\begin{bmatrix}\delta\nu_1\Sigma_{f,1}(\overline{r'},\omega)\\ \delta\nu_2\Sigma_{f,2}(\overline{r'},\omega)\end{bmatrix}.\quad(8)$$

The same GFEM is used to discretize the neutron noise equation (Hosseini and Vosoughi, 2012). By considering the neutron noise source in group 2 and using the GFEM, Eq. (7) can be reformed:

$$\sum_{e=1}^{E}\Bigg[\iint_{\Omega^{(e)}}d\Omega D_1\nabla N^{(e)}(\bar{r})\nabla N^{(e)T}(\bar{r})G^{(e)}_{2\to1}-\Sigma_1^{(e)}\iint_{\Omega^{(e)}}d\Omega N^{(e)}(\bar{r})N^{(e)T}(\bar{r})G^{(e)}_{2\to1}+\frac{\nu_2\Sigma^{(e)}_{f,2}}{k_{\mathrm{eff}}}\left(1-\frac{i\omega\beta_{\mathrm{eff}}}{i\omega+\lambda}\right)\times\iint_{\Omega^{(e)}}d\Omega N^{(e)}(\bar{r})N^{(e)T}(\bar{r})G^{(e)}_{2\to2}+\int_{\partial\Omega^{(e)V}}dsN^{(e)}(\bar{r})N^{(e)T}(\bar{r})\frac{G^{(e)}_{2\to1}}{2}\Bigg]=0,\quad(9)$$