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On a various soft computing algorithms for reconstruction of the neutron noise source in the nuclear reactor cores

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ABSTRACT

This paper presents a comparative study of various soft computing algorithms for reconstruction of neutron noise sources in the nuclear reactor cores. To this end, the computational code for reconstruction of neutron noise source is developed based on the Adaptive Neuro-Fuzzy Inference System (ANFIS), Decision Tree (DT), Radial Basis Function (RBF) and Support Vector Machine (SVM) algorithms. Neutron noise source reconstruction process using the developed computational code consists of three stages of training, testing and validation. The information of neutron noise sources and induced neutron noise distributions are used as output and input data of training stage, respectively. As input data, both the real and imaginary parts of numerical value of the neutron noise in the detector are used. In the present study, the neutron noise source of *absorber of variable strength* type is only considered. The neutron noise distributions in the detectors due to 2000 randomly generated neutron noise sources are calculated using the developed computational code based on Galerkin Finite Element Method (GFEM). As output data, the strength, frequency of occurrence and location (X and Y coordinates) of the considered neutron noise sources are used. The VVER-1000 reactor core is considered as the benchmarking problem for validation of performed simulation using developed computational code. All specifications of neutron noise source including strength, frequency and location of the neutron noise source are reconstructed with high accuracy. Finally, a sensitivity analysis of results to the number of active detectors in the reactor core is performed. A comparative study of the performance of different developed algorithms represents Decision Tree as the most appropriate one for reconstruction of the neutron noise source in the nuclear reactor cores.

1. Introduction

The neutron noise source is defined as small variations in a reactor core that lead to stationary fluctuation of the neutron flux distribution around its mean value. Timely recognition of the neutron noise source in the reactor cores is of great importance in reactor safety analysis. Many researchers have tried to develop different methods like *inversion*, *zoning*, *scanning* and Artificial Neural Network (ANN) for reconstruction of neutron noise source in the reactor cores (Demazière and Andhill, 2005; Hosseini and Vosoughi, 2013, 2014; Pázsit and Glöckler, 1984; Tambouratzis and Antonopoulos-Domis, 2002; Williams, 2013). In the relevant calculation of reconstruction of neutron noise source, an inverse problem should be solved using different numerical computational methods. Since the matrix coefficients in considered inverse problem are usually singular or badly-scaled, a direct solution leads to low accuracy of the results. Other algorithms like *scanning* and *zoning* used to reconstruct the neutron noise source suffer from drawbacks such as high computational cost (Demazière and Andhill, 2005; Pázsit and Glöckler, 1984). ANN may be used to reconstruct the neutron noise source in the reactor cores with high accuracy (Hosseini and Vosoughi, 2014). In the previously published papers by first author of the present paper, the developed computational codes based on ANN and *scanning* method were used to unfold the neutron noise sources of types absorber of variable strength and vibrating absorber with relatively high accuracy

Abbreviations: GFEM, Galerkin Finite Element Method; DYN-GFEM, Dynamical-Galerkin Finite Element Method; ANN, Artificial Neural Network; ANFIS, Adaptive Neuro-Fuzzy Inference System; DT, Decision Tree; RBF, Radial Basis Function; SVM, Support Vector Machine; SVRM, Support Vector Regression Machine; FVU, Fraction of Variance Unexplained; RMSE, Root Mean Square Error; CHAID, Chi-squared Automatic Interaction Detector; CART, Classification And Regression Tree.

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(Hosseini and Vosoughi, 2014). The drawback of ANN and *scanning* algorithms is that it requires high memory and computational costs. It leads to have a time consuming procedure for reconstruction of neutron noise source. A review of published papers on the reconstruction of the neutron noise source indicates that the neural network or its integration with scanning method compared with other aforementioned algorithms are more appropriate (Garis et al., 1998; Tambouratzis and Antonopoulos-Domis, 2002).

The purpose of the present paper is to develop a new computational code based on the soft computing algorithms including Adaptive Neuro-Fuzzy Inference System (ANFIS), Decision Tree (DT), Radial Basis Function (RBF) and Support Vector Machine (SVM) algorithms to reconstruct the neutron noise source of *absorber of variable strength* type in the VVER-1000 reactor core. A comparative study on the performance of the developed algorithms introduces the most appropriate algorithm for reconstruction of the neutron noise source in the reactor cores.

An outline of the remainder of present paper is as follows: In Section 2, we briefly introduce the mathematical formulation used to calculate neutron noise calculation in the reactor core. The developed algorithms to reconstruct the neutron noise source in the reactor core are presented in Section 3. The results of reconstruction of neutron noise source are given in Section 4. In Section 5, a sensitivity analysis of the results to the number of active detectors in the reactor core is performed. A discussion on the results and the merits of the proposed methods are presented in Section 6. Finally, Section 7 gives the concluding remarks.

2. Calculation of neutron noise distribution

The purpose of the present paper is the representation of the new soft computing algorithms for reconstruction of the neutron noise source in the reactor core using the neutron noise distribution in the detectors. To this end, the first order approximation of the neutron noise diffusion equation in 2-energy group was considered to calculate neutron noise distribution. The general form of the neutron noise diffusion equation, taking into account the neutron noise source as fluctuations in the scattering, absorption and fission macroscopic cross sections, is presented as Eq. (1) (Demazière and Andhill, 2005; Hosseini and Vosoughi, 2014; Itoh, 1986; Pázsit and Glöckler, 1984; Williams, 2013):

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

where all quantities are defined as usual. Also, the matrices and vectors in Eq. (1) are expressed as Eqs. (2)–(5):

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

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

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

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

The coefficient $\Sigma_1(\overline{r},\omega)$ used in Eq. (2) is defined by Eq. (6):

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

Neutron noise source is defined as product of perturbation ($\delta\Sigma$) in the neutron flux distribution. The required neutron flux distribution to calculate neutron noise source was obtained from the previously developed computational code (Hosseini and Vosoughi, 2013). In the present study, the neutron noise source of type of *absorber of variable strength* is considered, in which it is assumed that the fluctuation has occurred only in macroscopic absorption cross section. Various methods for solving the Eq. (1) may be used (Demazière and Andhill, 2005). Here, the *Green's function* technique is used (Demazière and Andhill, 2005) to calculate the neutron noise distribution in the reactor core. In this technique, the neutron noise distribution due to unit value, point like neutron noise source in the reactor core is calculated. The point like neutron noise source may be located inside the considered finite elements. The *Green*'s components due to different positions of unit value-point like neutron noise source are obtained from the solution of Eq. (7):

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

where $G_{g\to1}(\overline{r},\overline{r'},\omega)$ and $G_{g\to2}(\overline{r},\overline{r'},\omega)$ are the Green's function components of the energy groups 1 and 2 in the position $\overline{r}$ induced by the noise source in group g located in the position $\overline{r'}$, respectively. It is possible to consider the neutron noise source in the fast or thermal energy group.

In the present study, the Green's function components of the energy groups 1 and 2 in different elements were calculated by the solution of Eq. (7) using Galerkin Finite Element Method (GFEM) (Hosseini and Vosoughi, 2012). The fast and thermal neutron noise distributions were calculated via integral of product of the Green's function components in neutron noise source on the whole domain of the reactor core as in Eq. (8):

$$\begin{bmatrix}\delta\phi_1(\overline{r},\omega)\\ \delta\phi_2(\overline{r},\omega)\end{bmatrix}=\begin{bmatrix}\int[G_{1\to1}(\overline{r},\overline{r'},\omega)]S_1(\overline{r'},\omega)]+\int[G_{2\to1}(\overline{r},\overline{r'},\omega)S_2(\overline{r'},\omega)]d\overline{r'}\\ \int[G_{1\to2}(\overline{r},\overline{r'},\omega)]S_1(\overline{r'},\omega)]+\int[G_{2\to2}(\overline{r},\overline{r'},\omega)S_2(\overline{r'},\omega)]d\overline{r'}\end{bmatrix}. \quad (8)$$

If only the thermal macroscopic absorption cross section is perturbed, Eq. (8) will be reduced to Eq. (9):

$$\begin{bmatrix}\delta\phi_1(\overline{r},\omega)\\ \delta\phi_2(\overline{r},\omega)\end{bmatrix}=\begin{bmatrix}\int[G_{2\to1}(\overline{r},\overline{r'},\omega)S_2(\overline{r'},\omega)]d\overline{r'}\\ \int[G_{2\to2}(\overline{r},\overline{r'},\omega)S_2(\overline{r'},\omega)]d\overline{r'}\end{bmatrix}. \quad (9)$$

Here, it was assumed that the neutron noise source induced only by perturbation of the thermal energy group. Therefore, the neutron noise distribution in the reactor core was calculated by Eq. (9).

The purpose of the present paper was the representation of the new soft computing algorithms for reconstruction of the neutron noise source. The neutron noise distribution was calculated using the previously developed DYN-GFEM computational code (Hosseini and Vosoughi, 2012, 2016). The calculated neutron noise distribution in the VVER-1000 reactor core (FSAR, 2003) was used as input data of training stage of soft computing algorithms.

To validate the calculation of the neutron noise distribution, the benchmark problem that consists of a full-size VVER-1000 core with 163 fuel assemblies (FSAR, 2003) was considered. As shown in Fig. 1, VVER assemblies are hexagonal in shape and consist of 331 lattices locations in a hexagonal array. The hexagonal lattice pitch of the assembly cell is 23.6 cm. Each assembly contains 311