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Development of High-Speed Neutron Noise Simulator based on High order Nodal Expansion Method for Hexagonal Geometry in Frequency-Domain

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ABSTRACT

Improvement of reactor safety through simulation and analysis of power reactor noise requires the development of the neutron noise computation codes. The aim of this study is to create a neutron noise simulator for hexagonal geometry reactors. In this research, the SD-HACNEM (Sharif Dynamic - High order Average Current Nodal Expansion Method) simulator is enhanced to solve the steady-state neutron diffusion equation and neutron noise equation in the frequency-domain for two-dimensional hexagonal geometry using the high-order nodal expansion method. Initially, calculations are carried out for the steady-state. To minimize discretization errors, the degree of flux expansion polynomials is increased from 3rd to 5th, taking into account nodes the size of a fuel assembly for both ACNEM (Average Current Nodal Expansion Method) and HACNEM (High-order Average Current Nodal Expansion Method). The validation of the ACNEM and HACNEM is performed by comparing the results with verified references for the IAEA-2D benchmark problem reactor. The steady-state numerical results show that the use of HACNEM provides more accuracy compared with ACNEM, without reducing the size of the nodes. In the main part of the present study, neutron noise calculations are performed in the frequency-domain for two types of noise sources including absorber with variable strength and ILOFAIP (Inadvertent Loading and Operation of a Fuel Assembly in an Improper Position). The results are benchmarked through simulation at zero frequency and adjoint calculations. The numerical results show that the use of the high-order nodal expansion method is effective for the simulation of neutron noise in a hexagonal reactor.

Keywords: Neutron noise; Nodal expansion method; Hexagonal geometry; Frequency-domain.

1. Introductions

Safety systems and design features are implemented in a nuclear power plant to manage potential events and accidents. The activation or intervention of these systems depends on the occurrence of an initiating event. Recent advancements, such as the analysis of fluctuations in neutronic and

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thermal-hydraulic noise signals, have made it possible to predict the likelihood of an initiating event during standard operational conditions. By using this methodology, it is feasible to prevent the occurrence of such events through the application of appropriate protocols. In a nuclear reactor, fluctuations in neutronic and thermal-hydraulic parameters can be detected even under steady-state and full-power conditions. These fluctuations are referred to as power reactor noise and may originate from various sources, such as mechanical vibrations of components, coolant boiling, and temperature changes, among others [1,2].

By monitoring and analyzing the fluctuations, the operator can detect abnormal in a nuclear power plant to prevent events from occurring without causing any external disturbance to the system or compromising plant safety [3,4]. Exploring the theoretical aspects of neutron noise is essential for interpreting experimental results and elucidating atypical directivity patterns observed within the reactor environment. Sources of neutron noise can include a fuel assembly that is not properly positioned in the reactor core, variable-strength absorbers, minor changes in the absorption or scattering materials within the reactor core, and vibrations of the control rods [2,5]. The development of simulators for neutron noise simulation and analysis is necessary. Due to the critical role of neutron noise analysis in nuclear reactor safety, numerous studies have been conducted in this area. In recent years, various numerical tools have been utilized to create a neutron noise simulator [6-11]. Demazière [6] utilized the finite difference method (box method) to discretize the two-dimensional, two-group neutron noise equations in the frequency domain. The simulator developed was tailored for reactor cores with rectangular geometries but it is not suitable for hexagonal geometries.

In 2010, Malmir [8] developed a neutron noise simulator for hexagonal geometry using the finite difference method. In 2011, Larsson used the analytical nodal method to discretize the two-dimensional, two-group neutron noise equations in the frequency-domain. In 2018 Hosseini used the nodal expansion method (NEM) to discretize the same Equs. (7,9). According to the research conducted by Hosseini et al. [9], the use of nodes sized like a fuel assembly, along with the application of zero-order flux expansion, is likely to result in significant errors. Recently, many studies have been conducted on the simulation and analysis of the power reactor noise using various frequency and time domain tools such as PARCS and CORE-SIM codes [1], S3K [12,13], and DYN3D [14].

The studies mentioned highlight the significance of developing and enhancing power reactor noise simulators for effective noise analysis. More recently, the SD-HACNEM neutron noise simulator [15] was developed to perform calculations for rectangular geometry. In this work, a new ability was added to SD-HACNEM in order to perform calculations for hexagonal geometry. In order to increase the accuracy of the results the flux expansion order was increased. In other words, the calculations were performed for hexagonal geometry using the high-order nodal expansion method. The nodal expansion method is one type of nodal method in which average partial currents on the surfaces are used [16,17].

The advantages of the nodal expansion method, when compared to finite difference and finite element methods, include cost-effective calculations and a reduction in the execution time for simulated model problems [18,19]. Also, the nodal expansion method is more convergent than analytical nodal method [20]. The high-order average current nodal expansion method has been evaluated by Putney [19] for rectangular and hexagonal geometries in detail. In the previous published paper, SD-HACNEM simulator [15] for neutron noise simulation in the rectangular geometry reactors was discussed. It is important to note that in this work, the SD-HACNEM simulator was therefore updated to solve the steady-state neutron diffusion equation and neutron noise equation in the frequency-domain for two-dimensional hexagonal geometry using the high-order nodal expansion method.

2. Research theories

2.1. Steady-state calculation

Steady-state calculations are necessary for two reasons. First, steady-state results serve as inputs for neutron noise calculations. Second, one of method of verifying neutron noise calculations involves comparing the neutron noise results at zero frequency with the steady-state results. Therefore, this section will present the discretization of the neutron diffusion equation using the average current nodal expansion method. Specifically, fifth-degree polynomials will be used in the flux expansion. After applying the discretization approach proposed by Putney [19], the following equations are derived.

$$\left[\frac{4}{H}C_{g5}^{m}+\Sigma_{rg}^{m}\right]\Phi_{g}^{m}=\sum_{\substack{g'=1\\g'\neq g}}^{G}\Sigma_{sg'g}^{m}\,\Phi_{g'}^{m}+\frac{\chi_g}{K_{eff}}\sum_{g'=1}^{G}\nu\Sigma_{fg'}^{m}\,\Phi_{g'}^{m}$$
$$+\sum_{\substack{s=r\,l\\w=x\,u\,v}}\frac{2}{3H}\left(1-C_{g1}^{m}-C_{g2}^{m}-2C_{g3}^{m}-2C_{g4}^{m}\right)j_{gws}^{-m} \tag{1}$$

$$\begin{bmatrix}j_{gxr}^{+m}\\j_{gxl}^{+m}\\j_{gur}^{+m}\\j_{gul}^{+m}\\j_{gvr}^{+m}\\j_{gvl}^{+m}\end{bmatrix}=\begin{bmatrix}C_{g1}^{m}&C_{g2}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g5}^{m}&C_{g6}^{m}&C_{g7}^{m}&C_{g7}^{m}\\C_{g2}^{m}&C_{g1}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g5}^{m}&-C_{g6}^{m}&-C_{g7}^{m}&-C_{g7}^{m}\\C_{g4}^{m}&C_{g3}^{m}&C_{g1}^{m}&C_{g2}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g5}^{m}&C_{g7}^{m}&C_{g6}^{m}&C_{g7}^{m}\\C_{g3}^{m}&C_{g4}^{m}&C_{g2}^{m}&C_{g1}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g5}^{m}&-C_{g7}^{m}&-C_{g6}^{m}&-C_{g7}^{m}\\C_{g4}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g1}^{m}&C_{g2}^{m}&C_{g5}^{m}&C_{g7}^{m}&C_{g7}^{m}&C_{g6}^{m}\\C_{g3}^{m}&C_{g4}^{m}&C_{g3}^{m}&C_{g4}^{m}&C_{g2}^{m}&C_{g1}^{m}&C_{g5}^{m}&-C_{g7}^{m}&-C_{g7}^{m}&-C_{g6}^{m}\end{bmatrix}\begin{bmatrix}j_{gxr}^{-m}\\j_{gxl}^{-m}\\j_{gur}^{-m}\\j_{gul}^{-m}\\j_{gvr}^{-m}\\j_{gvl}^{-m}\\\Phi_{g}^{m}\\d_{gx}^{m}\\d_{gu}^{m}\\d_{gv}^{m}\end{bmatrix} \tag{2}$$

$$d_{gx}=\frac{\left(\alpha_g^m+\beta_g^m\right)Q_{gx}^m-\beta_g^mQ_{gu}^m-\beta_g^mQ_{gv}^m}{\left(\alpha_g^m-\beta_g^m\right)\left(\alpha_g^m+2\beta_g^m\right)}\;;d_{gu}$$
$$=\frac{-\beta_g^mQ_{gx}^m+\left(\alpha_g^m+\beta_g^m\right)Q_{gu}^m-\beta_g^mQ_{gv}^m}{\left(\alpha_g^m-\beta_g^m\right)\left(\alpha_g^m+2\beta_g^m\right)}; \tag{3}$$

These equations are the nodal balance equation, nodal coupling equation, and the high-order coefficients equations of the flux expansion, respectively. The parameters of the above equations can be found in Putney [19]. Reference [21] and discretization approach similar to forward equations are also used to calculate the adjoint equations.

2.2. Neutron noise calculation

In this section, the neutron noise equation in the frequency-domain is discretized using the high-order nodal expansion method. The general form of neutron noise equations in the two energy groups is based on references [2,5]. Generally, the noise source is considered as a perturbation in the macroscopic cross-sections. To derive the forward and adjoint neutron noise equations, a perturbation in the time-dependent equations macroscopic cross-sections is introduced and subtracted from the steady-state equations. This process results in the neutron noise equations outlined in Eqs. (4-6).

$$\begin{bmatrix} \Sigma_1^m(\omega)+\frac{4}{H}C_{15}^m & -\frac{\nu\Sigma_{f\,2}^{m\,0}}{k_{eff}}(1-\frac{i\omega\beta_{eff}}{i\omega+\lambda}) \\ -\Sigma_{s1\,2}^{m\,0} & \frac{4}{H}C_{25}^m+\frac{i\omega}{v_2}+\Sigma_{a\,2}^{m\,0} \end{bmatrix}\begin{bmatrix}\delta\Phi_1^m(\omega)\\ \delta\Phi_2^m(\omega)\end{bmatrix}$$

$$-\begin{bmatrix} \frac{2}{3H}(1-C_{11}^m-C_{12}^m-2C_{13}^m-2C_{14}^m) & 0 \\ 0 & \frac{2}{3H}(1-C_{21}^m-C_{22}^m-2C_{23}^m-2C_{24}^m) \end{bmatrix}\begin{bmatrix} \sum\limits_{\substack{w=x\,u\,v\\ s=r\,l}} \delta j_{1ws}^{-m}(\omega) \\ \sum\limits_{\substack{w=x\,u\,v\\ s=r\,l}} \delta j_{2ws}^{-m}(\omega) \end{bmatrix}$$

$$= \begin{bmatrix}-\Phi_1^{m\,0}\\ \Phi_1^{m\,0}\end{bmatrix}\delta\Sigma_{s1\,2}^m(\omega)-\begin{bmatrix}\Phi_1^{m\,0} & 0\\ 0 & \Phi_2^{m\,0}\end{bmatrix}\begin{bmatrix}\delta\Sigma_{a1}^m(\omega)\\ \delta\Sigma_{a2}^m(\omega)\end{bmatrix}+(1-\frac{i\omega\beta_{eff}}{i\omega+\lambda})\begin{bmatrix}\Phi_1^{m\,0} & \Phi_2^{m\,0}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\delta\nu\Sigma_{f\,1}^m(\omega)\\ \delta\nu\Sigma_{f\,2}^m(\omega)\end{bmatrix} \tag{4}$$

$$\begin{bmatrix}\delta j_{gxr}^{+m}(\omega)\\ \delta j_{gxl}^{+m}(\omega)\\ \delta j_{gur}^{+m}(\omega)\\ \delta j_{gul}^{+m}(\omega)\\ \delta j_{gvr}^{+m}(\omega)\\ \delta j_{gvl}^{+m}(\omega)\end{bmatrix}=\begin{bmatrix} C_{g1}^m & C_{g2}^m & C_{g4}^m & C_{g3}^m & C_{g4}^m & C_{g3}^m & C_{g5}^m & C_{g6}^m & C_{g7}^m & C_{g7}^m \\ C_{g2}^m & C_{g1}^m & C_{g3}^m & C_{g4}^m & C_{g3}^m & C_{g4}^m & C_{g5}^m & -C_{g6}^m & -C_{g7}^m & -C_{g7}^m \\ C_{g4}^m & C_{g3}^m & C_{g1}^m & C_{g2}^m & C_{g4}^m & C_{g3}^m & C_{g5}^m & C_{g7}^m & C_{g6}^m & C_{g7}^m \\ C_{g3}^m & C_{g4}^m & C_{g2}^m & C_{g1}^m & C_{g3}^m & C_{g4}^m & C_{g5}^m & -C_{g7}^m & -C_{g6}^m & -C_{g7}^m \\ C_{g4}^m & C_{g3}^m & C_{g4}^m & C_{g3}^m & C_{g1}^m & C_{g2}^m & C_{g5}^m & C_{g7}^m & C_{g7}^m & C_{g6}^m \\ C_{g3}^m & C_{g4}^m & C_{g3}^m & C_{g4}^m & C_{g2}^m & C_{g1}^m & C_{g5}^m & -C_{g7}^m & -C_{g7}^m & -C_{g6}^m \end{bmatrix}$$

$$\times\begin{bmatrix}\delta j_{gxr}^{-m} & \delta j_{gxl}^{-m} & \delta j_{gur}^{-m} & \delta j_{gul}^{-m} & \delta j_{gvr}^{-m} & \delta j_{gvl}^{-m} & \delta\Phi_g^m(\omega) & \delta d_{gx}^m(\omega) & \delta d_{gu}^m(\omega) & \delta d_{gv}^m(\omega)\end{bmatrix}^T \tag{5}$$

$$\begin{bmatrix}\alpha_g^m & \beta_g^m & \beta_g^m\\ \beta_g^m & \alpha_g^m & \beta_g^m\\ \beta_g^m & \beta_g^m & \alpha_g^m\end{bmatrix}\begin{bmatrix}\delta d_{gx}^m\\ \delta d_{gu}^m\\ \delta d_{gv}^m\end{bmatrix}+\begin{bmatrix}d\_\alpha_g^m & d\_\beta_g^m & d\_\beta_g^m\\ d\_\beta_g^m & d\_\alpha_g^m & d\_\beta_g^m\\ d\_\beta_g^m & d\_\beta_g^m & d\_\alpha_g^m\end{bmatrix}\begin{bmatrix}d_{gx}^{m\,0}\\ d_{gv}^{m\,0}\\ d_{gv}^{m\,0}\end{bmatrix}=\begin{bmatrix}\delta Q_{gx}^m\\ \delta Q_{gu}^m\\ \delta Q_{gv}^m\end{bmatrix} \tag{6}$$

The operator forms of the forward neutron noise and adjoint neutron noise equations is defined as Eq. (7). Integrating over phase space leads to Eq. (8), where $d\Pi^m$ represents the spatial dimension in the nodal volume. Therefore, the frequency-domain neutron noise simulator can be validated by comparing the amplitude and phase of both sides of Eq. (8), or by utilizing adjoint calculations [6].

$$L\delta\phi=\delta S;\ \ L^\dagger\delta\phi^\dagger=\delta S^\dagger \tag{7}$$

$$\int[\delta\phi_1(r\ \ \omega)+\delta\phi_2(r\ \ \omega)]\,d\Pi^m$$
$$=\int\big[\phi_1(r)\delta\phi_1^\dagger(r\ \ \omega)$$
$$+\phi_2(r)\delta\phi_2^\dagger(r\ \ \omega)\big]\,d\Pi^m \tag{8}$$

2.3. IAEA-2D PWR benchmark rearctor

The IAEA-2D reactor is utilized to validate steady-state and neutron noise calculations. The core geometry is depicted in Fig. 1, with a fuel assembly lattice pitch of 20 cm. According to references [22,23], the Albedo boundary condition $\alpha=0{,}5$ is applied to this reactor core. The IAEA-2D macroscopic cross-section values in two energy groups are also provided in these references.

2.4. Numerical results and discussion

The IAEA reactor core calculations were conducted using ACNEM and HACNEM for nodes the size of a fuel assembly. Table 1 shows that the absolute value of neutron multiplication factor error (ε_k) for ACNEM and HACNEM is 517 *pcm* and 16 *pcm*, respectively. Additionally, the average relative percent error (RPE) of power for ACNEM and HACNEM is obtained 11.36% and 3.52%, respectively The maximum relative percent error of power for ACNEM and HACNEM is 23.97% and 8.88%, respectively. Therefore, by increasing the order of flux expansion and using fixed-size nodes, one can conclude that the accuracy of the calculations is significantly improved. The *RPE* distribution using ACNEM and HACNEM for the IAEA-2D reactor is comparable in Fig. 1. The values of reference [23, 24] are used to calculate the RPE in this figure.

The distribution of fast and thermal neutron fluxes for the IAEA-2D reactor, as computed by HACNEM, are shown in Fig. 2.

In Fig. 3, the thermal neutron noise distribution for a variable-strength absorber source is presented, as calculated by the developed neutron noise simulator known as SD-HACNEM. In this calculation, a perturbation of 0,0001cm^{-1} at a frequency of 0.01 Hz has been applied to the thermal absorption cross-section of the central fuel assembly.

In this study, the ILOFAIP neutron noise source is being investigated. The ILOFAIP source is a combination of two absorber sources with variable strengths and opposite signs. For the ILOFAIP simulation, two absorber sources with variable strengths are considered within the central fuel assembly and its neighboring assemblies. The strength of this perturbation is equal to the difference in the macroscopic cross-section of the two fuel assemblies, and the frequency of this source is 0.01 Hz. The distribution of the ILOFAIP neutron noise is visible in Fig. 4. the neutron noise equation is linear with respect to the perturbation and the response. Consequently, the response to the combination of two absorber sources with variable strength or ILOFAIP, is a superposition of the responses of the individual absorbers with variable strength.

Table 1. The neutron multiplication for IAEA-2D reactor.

Method	Expansion order	k_{eff}	$k^{\dagger}_{eff}$	ε_k(pcm)	RPE Ave.	RPE Max.	CPU-TIME (Sec)
ACNEM	3	1.00030	1.00030	-517	11.36	23.97	18
HACNEM	5	1.00534	1.00534	-16	3.52	8.88	28

* The reference value of the effective multiplication factor is 1.00551 [23, 24].

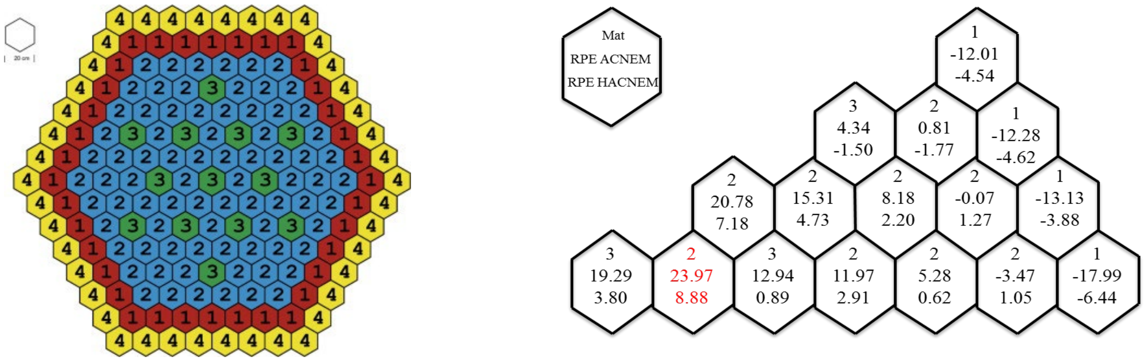


Fig. 1. IAEA-2D core arrangement and its *RPE* using ACNEM and HACNEM.

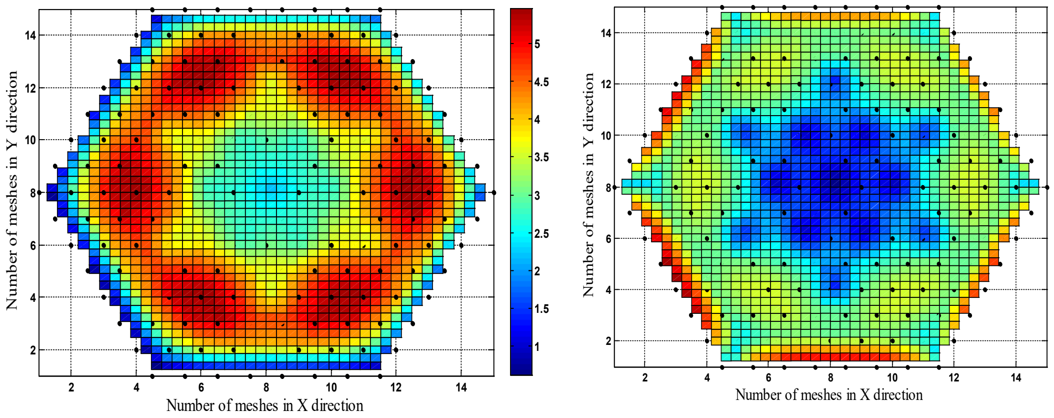
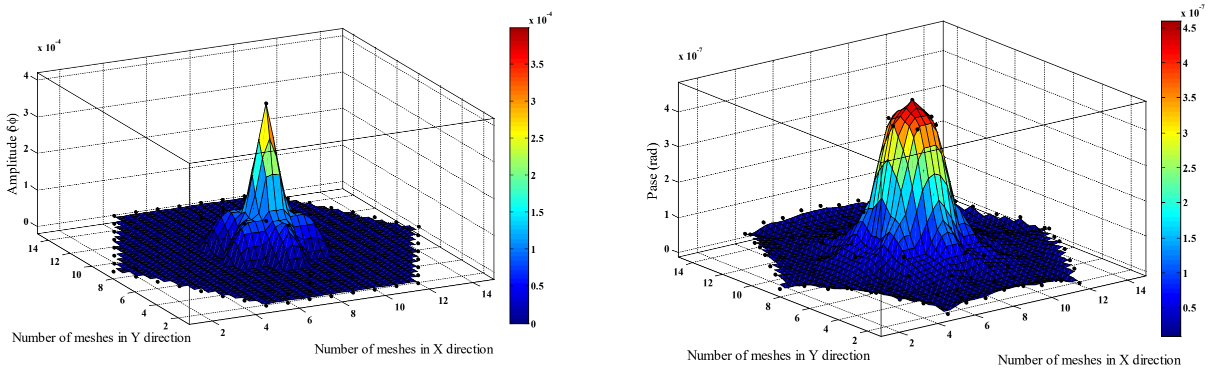


Fig. 2. Distribution of fast (left) and thermal (right) neutron flux calculated by HACNEM for IAEA-2D.

Forward



Adjoint

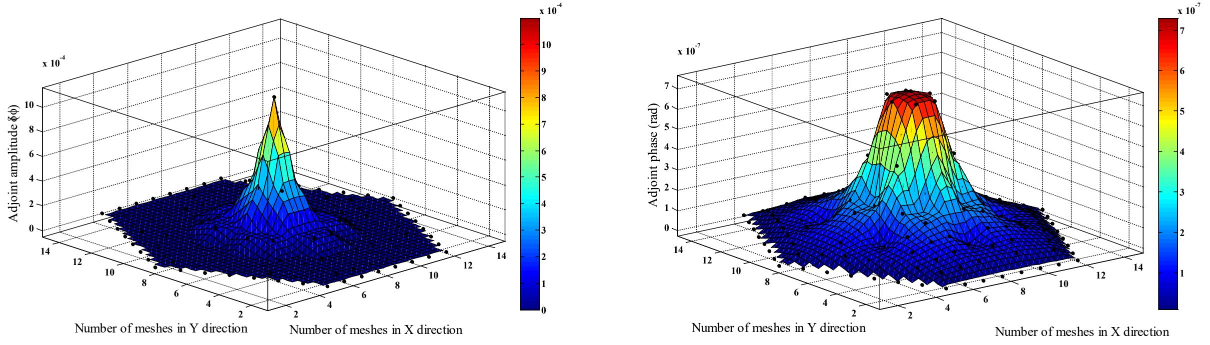


Fig. 3. Distribution of Thermal neutron noise amplitude (left) and phase (right) calculated with SD-HACNEM for IAEA-2D.

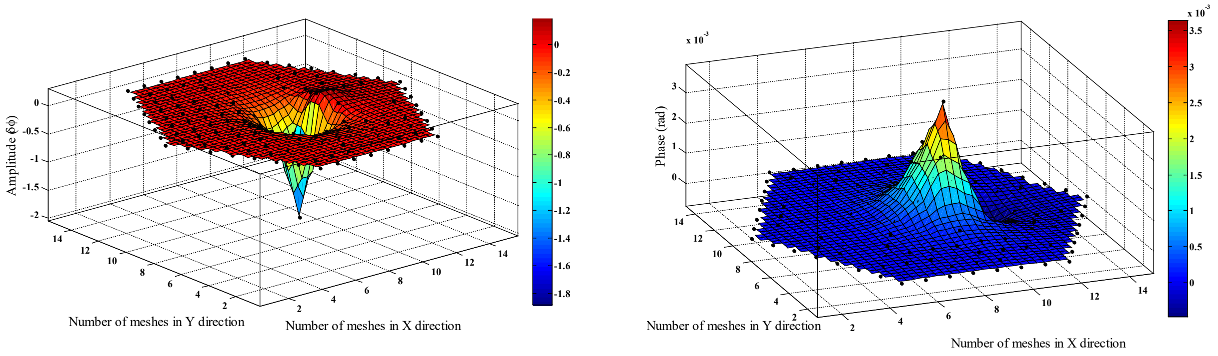


Fig. 4. Distribution of neutron noise amplitude (left) and phase (right) calculated with SD-HACNEM for ILOFAIP.

The qualitative comparison of the neutron noise figures obtained using SD-HACHEM with similar previous studies confirms the high-order nodal expansion method [8,9,11]. Neutron noise calculation at zero frequency is another method for verification of SD-HACHEM. In other words, the neutron noise calculations at zero frequency must match the results of the steady-state calculations. Fig. 5 shows the distribution of thermal and fast neutron noise at zero frequency and this figure completely matches with Fig. 2.

As previously mentioned, another method of verifying the calculations was performed using Eq. (8). Fig. 6 shows the amplitude of the left and right sides of Eq. (8) for a source of absorber with variable strength. Also, the phase of the left- and right-hand side of Eq. (8) for a source of absorber with variable strength are presented in this figure. Furthermore, based on the same figures, acceptable equality of the results (with an average difference of 6.66 %) is consistent. Since these figures demonstrate a minimal difference, it can be concluded that the high-order nodal expansion method is suitable for neutron noise calculations involving a source within the dimensions of a fuel assembly. Therefore, the verification used by qualitative comparison with references, zero-frequency neutron noise calculations, and the use of adjoint calculations (Eq. (8)) confirms the accuracy of the neutron noise simulation with the SD-HACNEM simulator.

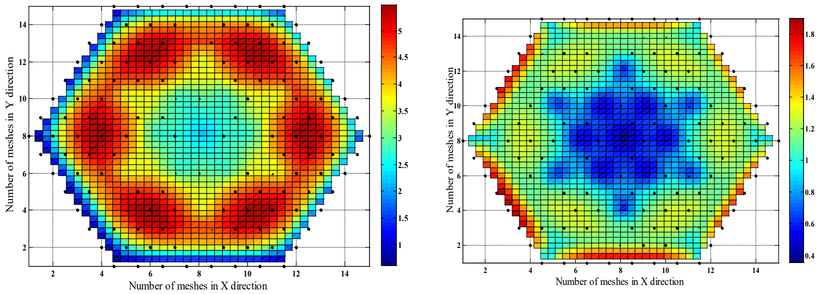
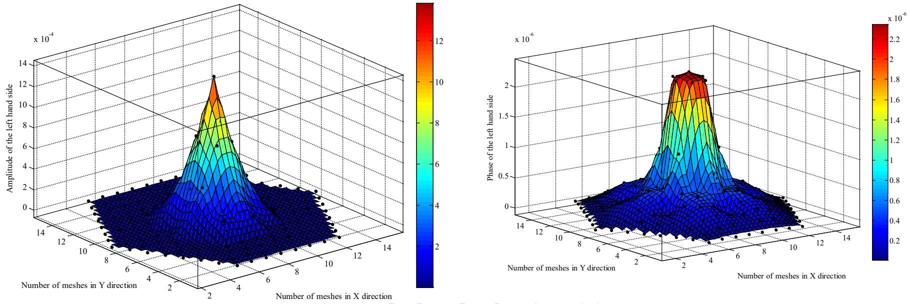


Fig. 5. Distribution of fast (left) and thermal (right) neutron noise calculated with SD-HACNEM at zero frequency.

Left-hand side of Eq. (8)



Right-hand side of Eq. (8)

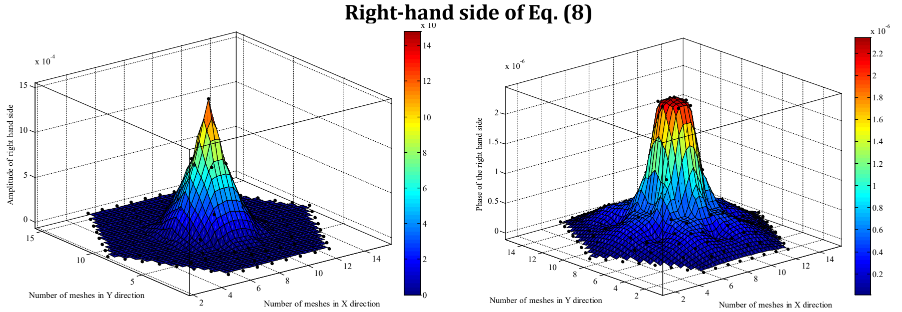


Fig. 6. The amplitude (left) and phase (right) of Eq. (8) for a source of absorber with variable strength 0.0001 cm^{-1} and frequency 0.01 Hz.

3. Conclusions

The limited number of detectors within the reactor core, combined with the need to replicate neutron noise generated by sources similar in size to a fuel assembly, necessitates the use of the average current nodal expansion method for neutron noise calculations. However, it is important to note that the calculation errors associated with the nodal expansion method can be significant due to the relatively large sizes of the nodes used. Therefore, implementing high-order expansion techniques is recommended to reduce these errors. Additionally, utilizing larger nodes in the nodal expansion method leads to a considerable decrease in both the computational time and costs associated with these calculations. In this paper, the higher-order average current nodal expansion method was used to derive the neutron noise equations, and then the SD-HACNEM hexagonal geometry core simulator was developed. To verify the steady-state calculations and neutron noise simulator, the IAEA-2D PWR reactor was used. By increasing the order of expansion of the polynomials from degree three to degree five, the average relative percent error in power improved from 11.36% to 3.52%. These results demonstrate that the simulator exhibits acceptable accuracy. Neutron noise calculations were conducted using SD-HACNEM for absorbers with variable strength and ILOFAIP neutron noise sources. Additionally, these calculations were validated through comparisons with verified references, zero-frequency calculations, and the application of adjoint calculations. The findings indicate that the high-order nodal expansion method is effective for simulating neutron noise in hexagonal reactors. In summary, the innovations of the current research can be outlined as follows:

- The use of nodes in the dimensions of the hexagonal fuel assembly with acceptable accuracy;
- The utilization of the fifth-degree polynomials in the discretization of neutron noise equations which makes HACNEM and SD-HACNEM precision considerably higher than ACNEM;
- Applying high-order flux expansion to simulate ILOFAIP neutron noise in the hexagonal reactor;
- Enhancing the SD-HACNEM neutron noise simulator for both rectangular and hexagonal geometry reactors.

By conducting this study, the SD-HACNEM simulator is now capable to simulate the neutron noise in rectangular or hexagonal geometries using the coarse mesh method, specifically the high-order nodal expansion method. For future research, a thermal-hydraulic noise simulator could be added to the current simulator to enable multi-physics evaluations of combined perturbations. Additionally, it could be used to develop an online perturbation identification tool based on deep learning algorithms.

Conflict of interest

The authors declare no potential conflict of interest regarding the publication of this work.

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