PHYSOR 2018: Reactor Physics paving the way towards more efficient systems
Cancun, Mexico, April 22-26, 2018

COMPARATIVE STUDY OF NEUTRON NOISE CALCULATIONS USING THE NEUTRON KINETICS CODE PARCS AND THE NEUTRON NOISE SIMULATOR CORE SIM

N. Olmo-Juan[1], C. Demazière[2], T. Barrachina[1], R. Miró[1] and G. Verdú[1*]

[1]Institute for Industrial, Radiophysical and Environmental Safety (ISIRYM)
Universitat Politècnica de València. Camí de Vera s/n 46021, València, Spain

[2]Chalmers University of Technology, Department of Applied Physics, Division of Subatomic and Plasma Physics, SE-412 96 Gothenburg, Sweden

nioljua@iqn.upv.es, demaz@chalmers.se, tbarrachina@iqn.upv.es, rmiro@iqn.upv.es, gverdu@iqn.upv.es

ABSTRACT

Fluctuations are observed in the recording of any process parameter in a nuclear reactor even when operating at full power and steady-state conditions. These fluctuations (also called noise) are due to, for example, turbulence, coolant boiling, mechanical vibrations, etc. The monitoring of those parameters allows detecting, using existing instrumentation and without introducing any external perturbation to the system, possible anomalies before they have any inadvertent effect on plant safety and availability. In the proposed work, the time-domain PARCS code was used to model the effect of stationary perturbations in nuclear reactors. The results of such simulations were compared to the results of simulations performed in the frequency domain using the tool developed by Chalmers University of Technology called CORE SIM. The development of a few test cases based on a real reactor model were undertaken in order to compare the time-domain and the frequency-domain simulations. A methodology aimed at comparing these two different types of tools was established. It was demonstrated that PARCS, although not primarily developed for such calculations, can reproduce neutron noise patterns for reasonable frequencies. Nevertheless, it was also observed that unphysical results were occasionally obtained.

KEYWORDS: time dependent, frequency domain, diffusion equation, noise analysis

1. INTRODUCTION

The analysis of the neutron noise is of great interest to the nuclear industry. In general, neutron noise arises from the fluctuations originating from mechanical vibrations, coolant boiling, turbulence, etc. The monitoring of the effect of such fluctuations onto the neutron flux offers the possibility to early detect anomalies and if adequate inversion techniques are implemented, to make a fingerprinting of the anomaly [1].

A new Horizon2020 project funded by the European Commission was recently launched along those lines. The project, coordinated by Chalmers University of Technology, is called CORTEX (COre

monitoring Techniques and EXperimental validation and demonstration). The ambition of the project [2] is to develop neutron noise-based core monitoring techniques to be used in commercial reactors with the aim to help utilities to early detect and characterize anomalies. The utilities could then take proper actions before such anomalies have inadvertent effects on plant safety and availability.

The analysis of these oscillations requires the prior determination of the reactor transfer function. This reactor transfer function gives the reactor response to predetermined perturbations. Two different approaches can be applied for such a purpose: calculations in the time domain or in the frequency domain.

The modelling in the frequency domain is usually done using dedicated tools, resolving separately the static neutron flux and the neutron noise. In the time domain on the other hand, simulations are carried out using existing neutron kinetics code without separating the static and the fluctuating parts. Such time dependent tools were not originally developed for modelling fluctuations of the neutron flux, but a few recent attempts have been reported in the literature [3]. There is thus a need to demonstrate whether such time dependent tools provide physically-sound results, using as a reference the frequency-based tools.

In this paper, a comparative study of these two methodologies is presented. The tools chosen for the comparison are the time domain based code PARCSv3.2 [4], which is the NRC reference neutron diffusion code; and the frequency domain tool CORE SIM [5], a neutron noise simulator developed by Chalmers University of Technology. Two different types of perturbations were considered: an absorber of variable strength and a travelling perturbation.

The paper is structured as follows. First, the time dependent diffusion equations and their resolution are presented, followed by the frequency domain diffusion equations. The modelling strategies retained in the two codes used in this study are thereafter highlighted. The methodology developed to obtain the input parameter for each code is also given particular emphasis, including the requirements to model consistent cases between the two codes. Finally, the results are presented and discussed, and the main conclusions are summarized.

2. TIME DEPENDENT DIFFUSION EQUATION

The diffusion equation with two energy groups and six groups of precursors of delayed neutrons read, using standard notations, as follows [4]:

$$\frac{1}{v_1}\frac{\partial \phi_1(\boldsymbol{r},t)}{\partial t} = -\nabla\left(-D_1(\boldsymbol{r},t)\boldsymbol{\nabla}\phi_1(\boldsymbol{r},t)\right) - \left(\Sigma_{a1}(\boldsymbol{r},t) + \Sigma_{12}(\boldsymbol{r},t)\right)\phi_1(\boldsymbol{r},t)$$

$$+(1-\beta)\upsilon\Sigma_{f1}(\boldsymbol{r},t)\phi_1(\boldsymbol{r},t) + (1-\beta)\upsilon\Sigma_{f2}(\boldsymbol{r},t)\phi_2(\boldsymbol{r},t) + \sum_{k=1}^{6}\lambda_k C_k(\boldsymbol{r},t)\chi \qquad (1)$$

$$\frac{1}{v_2}\frac{\partial \phi_2(\boldsymbol{r},t)}{\partial t} = -\nabla\left(-D_2(\boldsymbol{r},t)\boldsymbol{\nabla}\phi_2(\boldsymbol{r},t)\right) - \Sigma_{a2}(\boldsymbol{r},t)\phi_2(\boldsymbol{r},t) + \Sigma_{12}(\boldsymbol{r},t)\phi_1(\boldsymbol{r},t) \qquad (2)$$

$$\frac{\partial C_k(\boldsymbol{r},t)}{\partial t} = \beta_k\upsilon\Sigma_{f1}\phi_1(\boldsymbol{r},t) + \beta_k\upsilon\Sigma_{f2}\phi_2(\boldsymbol{r},t) - \lambda_k C_k(\boldsymbol{r},t) \quad ; \quad k = 1,\dots,6 \qquad (3)$$

The diffusion coefficients, macroscopic cross-sections, thermal and fast fluxes and the concentration of the six groups of neutron precursors are space and time dependent parameters and variables. Bold letters are used to indicate vectors.

The code PARCSv3.2 solves these equations for 3-dimensional systems, both in cartesian or hexagonal geometries. Concerning the spatial discretization, different methods and options are available, such as the Finite Difference Method (FDM) or a nodal hybrid method combining the Analytical Nodal Method and the Nodal Expansion Method (HYBRID), among others.

3. FREQUENCY DOMAIN DIFFUSION EQUATION

In case of the frequency domain and following the implementation used in CORE SIM, the balance equations are derived from two-group diffusion theory but using only one group of delayed neutrons [5]:

$$\frac{1}{v_1}\frac{\partial \phi_1(\boldsymbol{r},t)}{\partial t} = -\nabla\big(-D_1(\mathbf{r})\nabla\phi_1(\boldsymbol{r},t)\big) - (\Sigma_{a1}(\boldsymbol{r},t) + \Sigma_r(\boldsymbol{r},t))\phi_1(\boldsymbol{r},t)$$

$$+(1-\beta)\upsilon\Sigma_{f1}(\boldsymbol{r},t)\phi_1(\boldsymbol{r},t) + (1-\beta)\upsilon\Sigma_{f2}(\boldsymbol{r},t)\phi_2(\boldsymbol{r},t) + \lambda C(\boldsymbol{r},t) \quad (4)$$

$$\frac{1}{v_2}\frac{\partial \phi_2(\boldsymbol{r},t)}{\partial t} = -\nabla\big(-D_2(\boldsymbol{r})\nabla\phi_2(\boldsymbol{r},t)\big) - \Sigma_{a2}(\boldsymbol{r},t)\phi_2(\boldsymbol{r},t) + \Sigma_r(\boldsymbol{r},t)\phi_1(\boldsymbol{r},t) \quad (5)$$

$$\frac{\partial C(\boldsymbol{r},t)}{\partial t} = \beta\upsilon\Sigma_{f1}(\boldsymbol{r},t)\phi_1(\boldsymbol{r},t) + \beta\upsilon\Sigma_{f2}(\boldsymbol{r},t)\phi_2(\boldsymbol{r},t) - \lambda C(\boldsymbol{r},t) \quad (6)$$

It should be noted that in this derivation, the system is considered to be critical in its mean with no external neutron source and that the diffusion coefficients are assumed to be time-independent [6].

Considering small fluctuations around the mean values, the time-dependent terms can be expressed as the sum of the steady-state value (i.e. the mean value) and the fluctuation around the mean value (i.e. the so-called noise):

$$X(\boldsymbol{r},t) = X_0(\boldsymbol{r}) + \delta X(\boldsymbol{r},t) \quad (8)$$

Applying a temporal Fourier transform, the following expression is obtained for the fluctuating part only:

$$\Big[\nabla\cdot\bar{\bar{D}}(\boldsymbol{r})\nabla + \bar{\bar{\Sigma}}_{dyn}^{crit}(\boldsymbol{r},\omega)\Big] \times \begin{bmatrix}\delta\phi_1(\boldsymbol{r},\omega)\\ \delta\phi_2(\boldsymbol{r},\omega)\end{bmatrix} =$$

$$\bar{\phi}_r(\boldsymbol{r})\delta\Sigma_r(\boldsymbol{r},\omega) + \bar{\bar{\phi}}_a(\boldsymbol{r})\begin{bmatrix}\delta\Sigma_{a1}(\boldsymbol{r},\omega)\\ \delta\Sigma_{a2}(\boldsymbol{r},\omega)\end{bmatrix} + \bar{\bar{\phi}}_f^{crit}(\boldsymbol{r},\omega)\begin{bmatrix}\delta\upsilon\Sigma_{f1}(\boldsymbol{r},\omega)\\ \delta\upsilon\Sigma_{f2}(\boldsymbol{r},\omega)\end{bmatrix} \quad (9)$$

The code CORE SIM solves these equations in Matlab using a LU PQ decomposition. It should also be noted that prior to performing noise calculations, CORE SIM estimates the static neutron flux and the corresponding eigenvalue using either the explicitly-restarted Arnoldi method or the power iteration

method with Wielandt's shift technique [5]. The computed eigenvalue is used to rescale the prompt neutron contributions, thus guaranteeing no drift in the mean.

4. METHODOLOGY

In the present work the methodology developed for comparing the results of the neutronics tools PARCSv3.2 and CORE SIM is detailed.

The case that will serve as the basis for this study corresponds to the neutronic configuration of a reference nuclear power plant.

4.2. Methodology for steady state cases

Before considering noise calculations, it has to be verified that the two codes used provide consistent results for the nominal steady-state core configuration.

The PARCS model and input file were first defined. An equivalent CORE SIM model was then derived. The input data needed by CORE SIM are the dimensions of an elementary node in the *x*-, *y*-, and *z*-directions and the value of the different cross sections for each node. Based on these data, CORE SIM solves the diffusion equation for the modelled reactor containing as many nodes as non-zero entries in the arrays of the cross-section sets.

The set of cross sections were obtained from PARCS runs by editing the cross-sections retrieved from the cross-sections files (nemtab/r files) at the corresponding thermal-hydraulic steady-state conditions.

For that purpose, the values of the cross-sections read by PARCS were printed to an external file making use of modifications implemented in the source code. Once printed, the data were reordered and written in a format directly readable in Matlab and CORE SIM. A program was created for this specific task.

Some tests were carried out to verify that the cross-sections printed by PARCS did include the correction due to the presence of Xenon in the reactor.

4.3. Methodology for transient cases

As regards the implementation of transient cases, two types of problems were investigated:

- Case of an absorber of variable strength.
- Case of a travelling perturbation in coolant density from the inlet to the outlet of a given fuel assembly.

The main difference between both cases is that in the first case the disturbance is restricted to a single node, for which the amplitude and phase of the disturbance can be arbitrarily set. On the other hand, in the case of a disturbance caused by a travelling perturbation, the determination of the amplitude and phase of the applied perturbation is slightly more involved, as explained hereafter.

It must be emphasized that CORE SIM is only capable of defining a perturbation in terms of cross-sections fluctuations.

While the CORE SIM tool is explicitly designed to perform this type of simulation, this is not the case for PARCS. Modelling this type of transients is thus a far from trivial exercise.

It has to be mentioned that since CORE SIM only uses one group of delayed neutron precursors, the same number of groups was adopted in PARCS.

4.3.1. Absorber of variable strength

The problem of an absorber of variable strength is by far the simplest problem of the two contemplated in this work. Due to the definition of the problem itself, the disturbance is confined to a single node for which only the values corresponding to the absorption cross section are modified in both energy groups.

The disturbance is induced as a function of time in the perturbed cross-sections as:

$$\Sigma = \Sigma_0\big(1 + A * sin(\omega t)\big) = \Sigma_0\big(1 + A * sin(2\pi f t)\big) \quad (10)$$

where Σ is the perturbed cross section, Σ_0 is the unperturbed (mean) value, A the amplitude and f the desired frequency.

The generation of an input file to CORE SIM for the case of a variable length absorber is relatively simple. Only the following is needed in addition to the data necessary to define the stationary case: effective fraction of delayed neutrons and the corresponding decay constant, and the frequency of the perturbation. The noise source is then simply introduced by defining an arbitrary amplitude for the perturbed cross-sections in the corresponding node. Because of the heterogeneous nature of the system of equation being solved, the induced neutron noise is directly proportional to the applied perturbation, explaining why the amplitude can be arbitrary chosen (and the phase set to zero to simplify even further the case).

4.3.2. Travelling perturbation

In this case, the perturbation is introduced by perturbing the coolant density in an entire channel in the following manner:

$$\mathrm{DENS}_i = \mathrm{DENS}_{i,0}\big(1 + A * sin(\omega t + \varphi)\big) = \mathrm{DENS}_{i,0}\big(1 + A * sin(2\pi f(t - \mathrm{k} * \Delta x/v))\big) \quad (11)$$

$\mathrm{DENS_i}$ and $\mathrm{DENS_{i,0}}$ represent the values of the perturbed and unperturbed densities, respectively. Due to the travelling nature of the perturbation, an axial phase shift φ between nodes exist. This axial phase shift can also be expressed as a function of the node axial position (k), the distance between nodes (Δx) and by the speed at which the fluid is travelling upwards in the channel (v).

However, including this perturbation is not a simple task, since it requires making changes to the source code of PARCSv3.2 and, subsequently, to the printing of the cross-sections interpreted by the code. This second step is essential because CORE SIM is only able to process nodal cross-sections as input.

Also, obtaining the amplitude of the oscillation for each cross-section is a complex task because the density affects all cross sections and they respond differently depending on the node and the type of cross sections. For this reason, a tool was developed. Knowing the actual oscillations at each point (which is an input data corresponding to the applied disturbance in density), the tool allows determining the resulting amplitude of the fluctuations in each cross-section.

Finally, once the amplitude of each cross-section has been obtained for each node in the disturbed channel, it is introduced into the CORE SIM input file. Due to the axial time delay of the applied perturbation, the corresponding phase in the frequency domain is defined using an exponential function as:

$$G_{i,frec} = G_{i,temp} * e^{-i*2\pi f*\Delta x*\frac{k}{v}} \quad (12)$$

where $\mathrm{G_{i,frec}}$ is the complex number associated to the amplitude and the phase of each cross-section perturbation in the frequency domain and $\mathrm{G_{i,temp}}$ is the amplitude in the temporal domain.

5. RESULTS AND DISCUSSION

In that section, a comparison between the results obtained by PARCSv3.2 and CORE SIM are presented. Steady-state simulations are first presented, followed by the results for the transient cases corresponding to a variable strength absorber and a travelling perturbation.

5.1. Steady state results

The purpose of the steady-state comparison is to clarify the appropriate numerical method to be used in PARCSv3.2 so that a faithful comparison between PARCSv3.2 and CORE SIM for the simulations of perturbations can be carried out. In addition, the level of necessary mesh refinement in CORE SIM is assessed.

Comparisons of k_{eff} and the axial flux profiles are reported hereafter. Several options were tested: the two types of spatial discretization in PARCSv3.2 (FDM or HYBRID), as well as two meshes in CORE SIM (a mesh identical to the one used in PARCSv3.2 and a refined mesh obtained by splitting each mesh cell in a given direction in two mesh cells). Assembly Discontinuity Factors (ADFs) were not considered in PARCSv3.2 because CORE SIM cannot account for ADFs at present.

Table I. Results of the comparison for k-effective.

	PARCS Hybrid	**PARCS FDM**	**CORE SIM**	**CORE SIM (double mesh)**
K-Effective:	1.000451	1.022211	1.022336	1.005247
		FDM vs CS	-12.5 pcm	

As can seen, differences in k_{eff} obtained between PARCSv3.2 and CORE SIM are very small when the FDM option in PARCS is chosen. This is explained by the fact CORE SIM is also based on finite differences.

It can be observed in Figures 1 and 2 that a better match is obtained when FDM is chosen as PARCS nodal kernel and when the simplest mesh for CORE SIM is used. It should also be noticed that the results using a refined mesh in CORE SIM and Hybrid method in PARCSv3.2 seems to be relatively close. However, in the following of this study, the option giving minimal errors is chosen. That is, the FDM option for PARCSv3.2 and the simple mesh in CORE SIM.

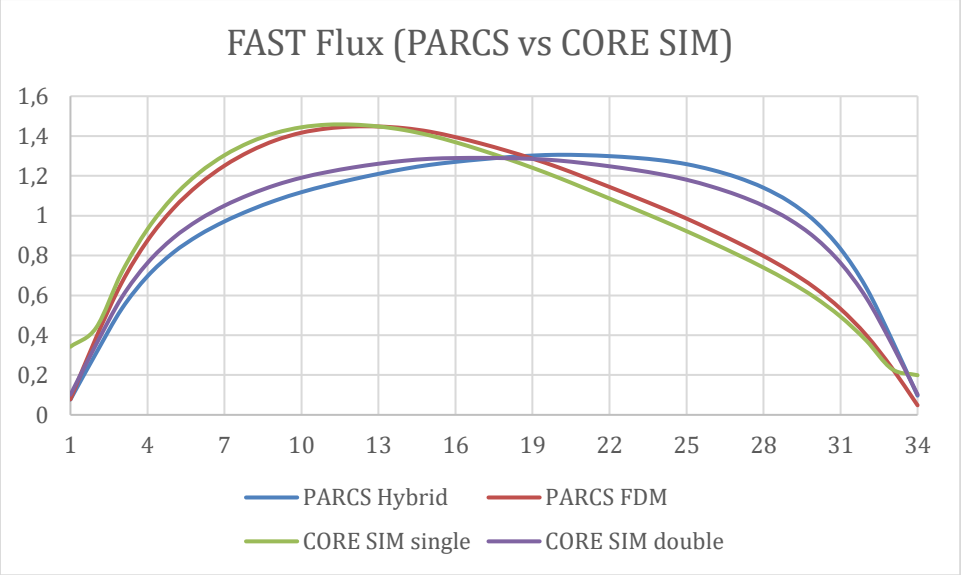

Figure 1. Comparison of the fast flux profiles using PARCSv3.2 and CORE SIM.

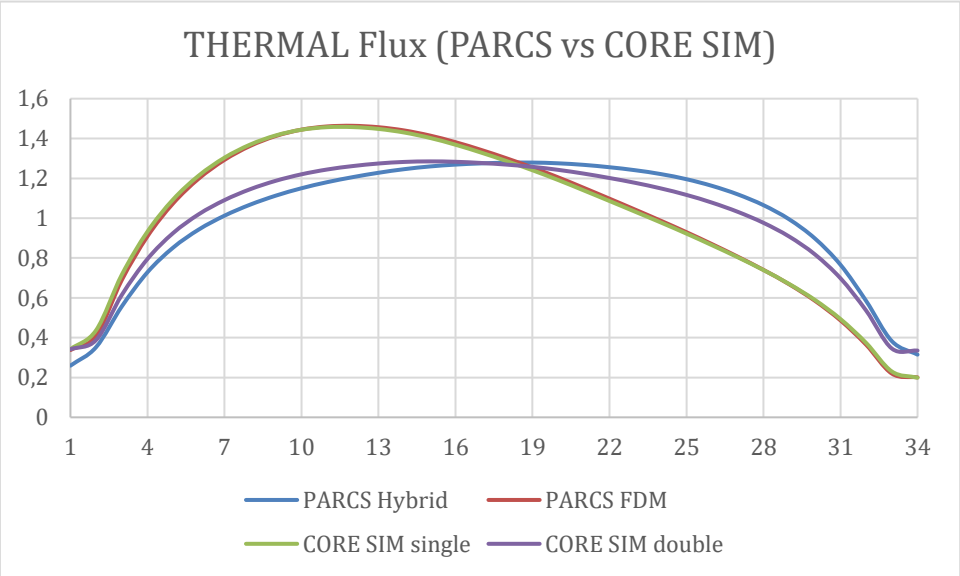

Figure 2. Comparison of the thermal flux profiles using PARCSv3.2 and CORE SIM.

5.2. Transient results

Once the steady-state results were obtained and the models in CORE SIM and PARCSv3.2 chosen, the transient simulations were undertaken. As earlier mentioned, two cases were considered: an absorber of variable strength and a travelling perturbation. For each case, a few situations were considered in order to test the influence of:

- The frequency of the perturbation: 1 Hz or 10 kHz,
- The amplitude of the perturbation: 1% or 5%,
- And the location of the perturbation: three different positions, from the center to the periphery of the core and located in the upper-left quarter of the core.

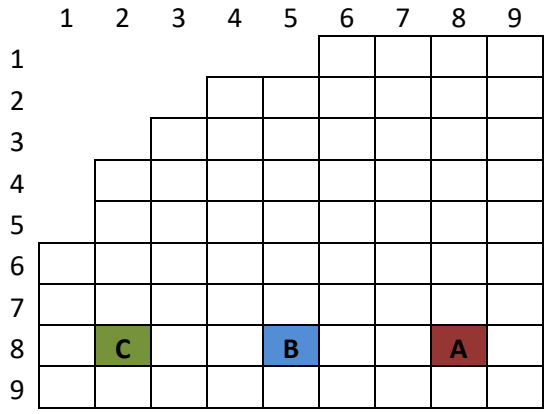

Figure 3. Upper-left quarter of the core showing location of the three positions studied.

The first objective of this study is to check whether similar trends are obtained in both codes. The results are thus presented in the following as spatial variations of the results along chosen characteristic directions across the core. It should be pointed out that in some specific nodes, large discrepancies were nevertheless obtained. For the sake of brevity, only two representative cases are reported in detail hereafter. A compilation of all the numerical results beyond these two cases are presented in the Appendix.

As can be seen in Figures 4 and 5 corresponding to the travelling perturbation case at point A at 1 Hz and 5% of amplitude, a really good fit is demonstrated for the spatial distribution of the amplitude and phase in thermal flux, thus leading to almost inexistent absolute error. The results corresponding to the fast flux (not reported here) are equivalent.

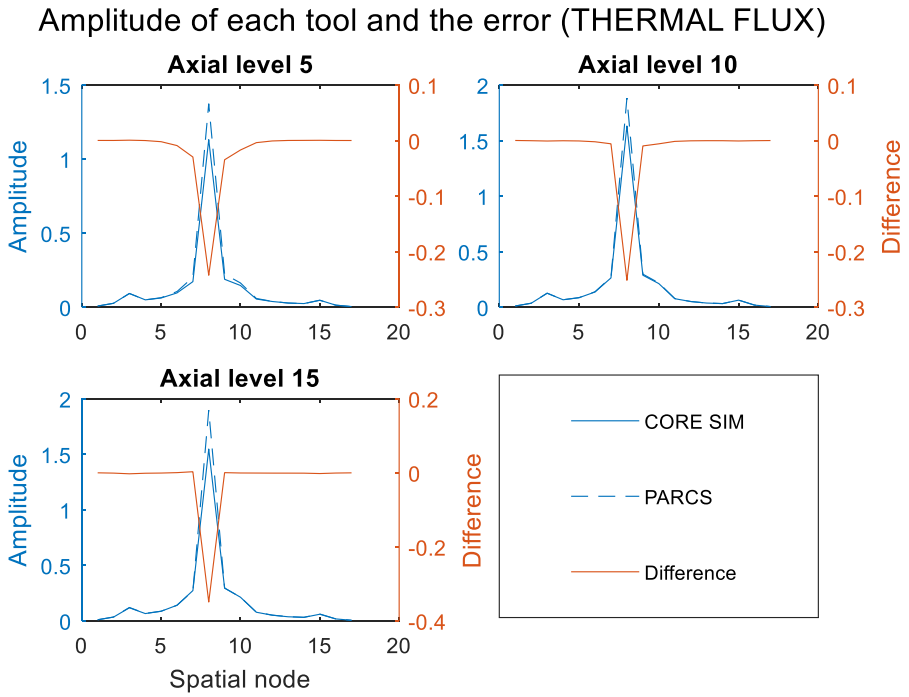

Figure 4. Amplitude of CORE SIM and PARCSv3.2 and corresponding absolute error obtained between the tools for the case of a travelling perturbation at 1 Hz, located at point A with a 5% amplitude.

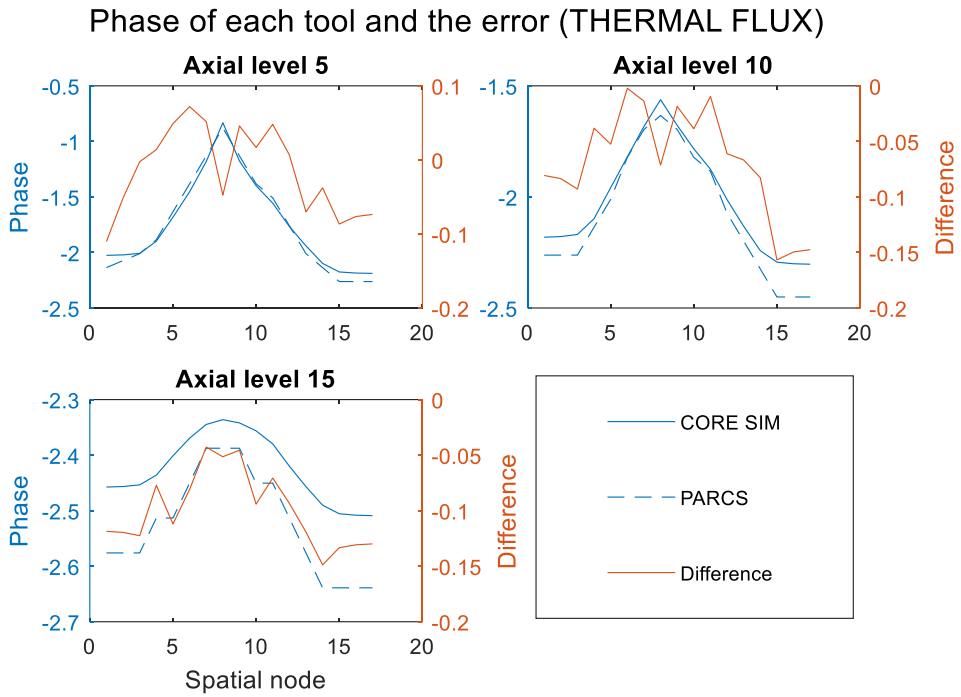

Figure 5. Phase of CORE SIM and PARCSv3.2 and corresponding absolute error obtained between the tools for the case of a travelling perturbation at 1 Hz, located at point A with a 5% amplitude.

It should be mentioned that some extra changes had to be done to the PARCSv3.2 source code, in order to increase the number of significant digits while requesting the edits of the flux values. This is explained by the fact that both the mean values and fluctuations are modelled in PARCS. Without such a modification the values extracted for the fluctuations would not be accurate enough and unphysical results in terms of induced neutron noise would be obtained.

The representative figures chosen for the absorber of variable strength correspond to the thermal flux for the case corresponding to the position A, at 1 kHz and 1% of amplitude. This perturbation is located on the 10th axial level from the bottom of the core (out of 34 possible levels). As it can be seen in Figure 6, the discrepancies between the two codes seem to be acceptable on the axial plane where the perturbation is located. Nevertheless, for axial planes further away from the introduced perturbation, large discrepancies are sometimes obtained, due to apparently unphysical results in the PARCS simulations.

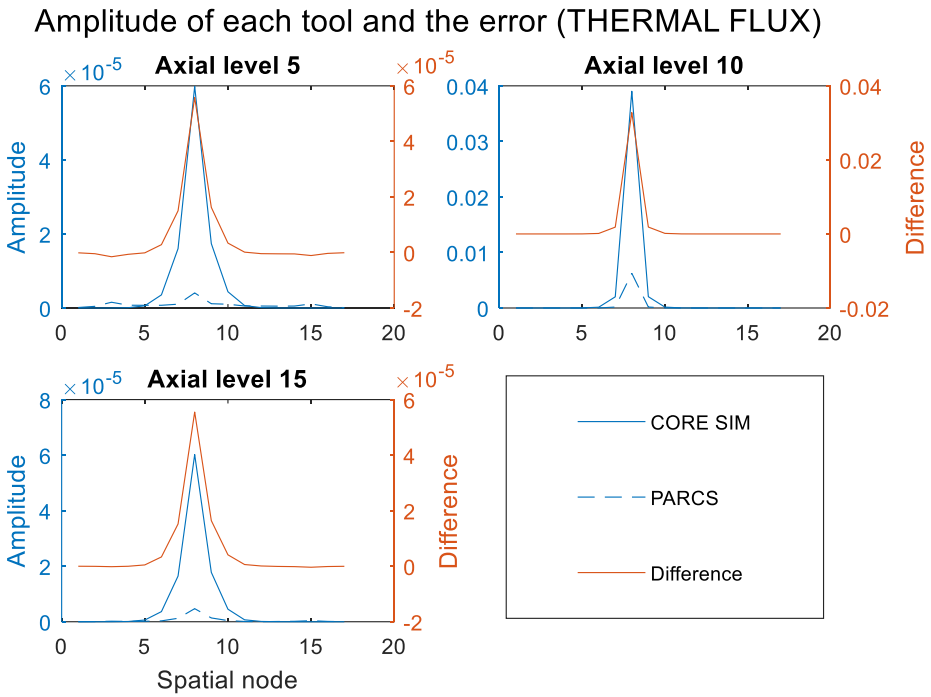

Figure 6. Amplitude of CORE SIM and PARCSv3.2 and corresponding absolute error obtained between the tools for the case of an absorber of variable strength at 10 kHz, located at point A with a 1% amplitude.

On the other hand, for the phase of the induced neutron noise, big discrepancies are observed, as illustrated in Figure 7. This might be explained by the difficulty in post-processing the PARCSv3.2 results with respect to the determination of the phase.

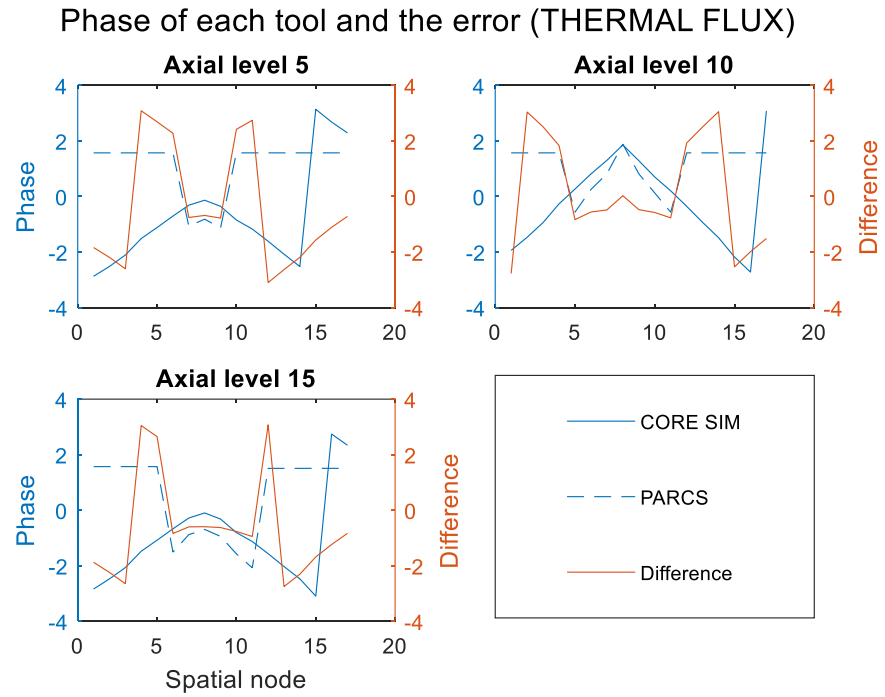

Figure 7. Phase of CORE SIM and PARCSv3.2 and corresponding absolute error obtained between the tools for the case of an absorber of variable strength at 10 kHz, located at point A with a 1% amplitude.

This study represents a first evaluation of the cases that PARCSv3.2 can faithfully model when considering neutron noise calculations. It was noticed in particular that frequencies closer to the usual time scales used in time-dependent calculations seem to provide much better results, than for very high frequencies. Although not reported in this paper, better results were also obtained for the most centered perturbations.

Finally, a compilation of the maximum errors and the RMS for all the simulations that were performed in this work is listed in Tables II and III in Appendix A. The errors corresponding to the amplitude are shown in relative terms (%) while the errors in the phase are given in radians. It should be noticed that for some of simulations, very large discrepancies in both the RMS and the maximum errors are obtained.

6. CONCLUSIONS

In this work, a methodology for comparing the results of neutron noise simulations using the time domain based code, PARCSv3.2, and frequency domain based code, CORE SIM, was developed. This required making changes to the PARCSv3.2 source code to: a) be able to introduce perturbations in the model, b) to edit the corresponding cross-sections and c) to edit the induced neutron flux with a significant number of digits.

The results obtained in this study demonstrate that PARCS, although not developed for that purpose, is able to provide a meaningful estimation of the induced neutron noise for reasonable frequencies (around 1 Hz), even if unphysical results are obtained at some positions within the core. For much higher frequencies, PARCS does not seem to faithfully reproduce the induced neutron noise.

ACKNOWLEDGMENTS

This work was carried out under the pre-doctoral contract FPI Subprogram 1 and mobility aids of the Universitat Politècnica de Valencia and the support of the Spanish Ministerio de Ciencia e Innovación under the project ENE2014-59442-P. The research leading to these results was also partially funded from the Euratom research and training programme 2014-2018 under grant agreement No 754316.

The first author wished to acknowledge all the support and personal help received from Profs. Christophe Demazière and Paolo Vinai, and all the staff of the Department of Applied Physics at Chalmers University of Technology during the first author's visit to Chalmers.

REFERENCES

1. I. Pázsit and C. Demazière, *Noise techniques in nuclear systems*, Chapter in the *Handbook of Nuclear Engineering*, D. Cacuci, Ed., ISBN 978-0-387-98150-5, Springer, Vol. 3 (2010).
2. "CORTEX WEBSITE," http://cortex-h2020.eu/
3. D. Chionis, A. Dokhane, L. Belblidia, M. Pecchia, G. Girardin, H. Ferroukhi, A. Pautz, "SIMULATE-3K Analyses of Neutron noise response to fuel assembly vibrations and thermal-hydraulics parameters fluctuations," Int. Conf. Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2017), Jeju, Korea, April 16-20, 2017 (2017).

4. T. Downar, Y. Xu, V. Seker. *DRAFT (01/16/12) PARCSv3.0 U.S. NRC Core Neutronics Simulator THEORY MANUAL*. Department of Nuclear Engineering and Radiological Sciences, University of Michigan, MI, USA (2012)
5. C. Demazière, "CORE SIM: A multi-purpose neutronic tool for research and education," *Annals of Nuclear Energy*, **38** (12), pp. 2698-2718 (2011).
6. V. Larsson and C. Demazière, "Comparative study of 2-group P1 and diffusion theories for the calculation of the neutron noise in 1D 2-region systems," Annals of Nuclear Energy, 36 (10), pp. 1574-1587 (2009).

APPENDIX A

Table II. Compilation of differences between CORE SIM and PARCSv3.2 for the absorber of variable strength case.

			ABSORBER OF VARIABLE STRENGTH											
		Frequency	**1 Hz**						**10 kHz**					
		Location	**A**		**B**		**C**		**A**		**B**		**C**	
		Amplitude	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**
Amplitude	**Fast**	**Max. Error**	38.21%	38.00%	38.52%	38.17%	38.49%	37.76%	16926%	50002%	19662%	24825%	74990%	12838%
		RMS	3.55%	3.51%	3.62%	3.55%	3.62%	3.58%	197%	216%	203%	209%	213%	191%
	Thermal	**Max. Error**	32.24%	33.08%	47.71%	48.67%	53.05%	55.01%	12264%	3976%	3068%	7278%	4218%	30126%
		RMS	2.26%	2.20%	2.34%	2.24%	2.32%	2.25%	146%	143%	138%	146%	149%	178%
Phase	**Fast**	**Max. Error**	0.5666	0.3267	1.2092	0.6796	0.7492	1.5118	3.1408	3.1408	3.1413	3.1413	3.1415	3.1415
		RMS	0.2448	0.2005	0.3387	0.3067	0.5201	0.5684	1.7469	1.7503	1.5778	1.5817	1.5419	1.5397
	Thermal	**Max. Error**	0.5669	0.3262	2.7081	0.641	0.7448	1.4501	3.1391	3.1408	3.1413	3.1413	3.1412	3.1412
		RMS	0.2441	0.2181	0.3899	0.2846	0.5227	0.6086	1.5472	1.5614	1.5666	1.5884	1.6223	1.6311

Table III. Compilation of differences between CORE SIM and PARCSv3.2 for the travelling perturbation.

			TRAVELLING PERTURBATION											
		Frequency	**1 Hz**						**10 kHz**					
		Location	**A**		**B**		**C**		**A**		**B**		**C**	
		Amplitude	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**	**5%**	**1%**
Amplitude	**Fast**	**Max. Error**	76%	296%	300%	334%	489%	4314%	7258%	15268%	40626%	35371%	43674%	18498%
		RMS	4.51%	14.14%	16.06%	32.74%	14.68%	69.07%	168%	178%	166%	194%	187%	190%
	Thermal	**Max. Error**	420%	352%	551%	564%	174%	4190%	6139%	27145%	46552%	24828%	8613%	13740%
		RMS	3.37%	13.50%	16.17%	33.16%	13.98%	69.86%	143%	151%	138%	140%	145%	154%
Phase	**Fast**	**Max. Error**	1.1521	1.3932	3.1415	3.1413	3.1246	3.1184	3.1398	3.1324	3.1413	3.1415	3.14	3.1406
		RMS	0.084	0.3412	2.5266	2.5354	0.3003	0.907	1.1009	1.0517	1.6151	1.5721	1.6922	1.664
	Thermal	**Max. Error**	1.4598	1.3575	3.1415	3.1413	3.1354	3.1304	3.1411	3.1401	3.1412	3.1414	3.1403	3.1411
		RMS	0.0832	0.3562	2.5132	2.5293	0.2782	0.8831	1.5099	1.4766	1.5547	1.2101	1.4647	1.4323