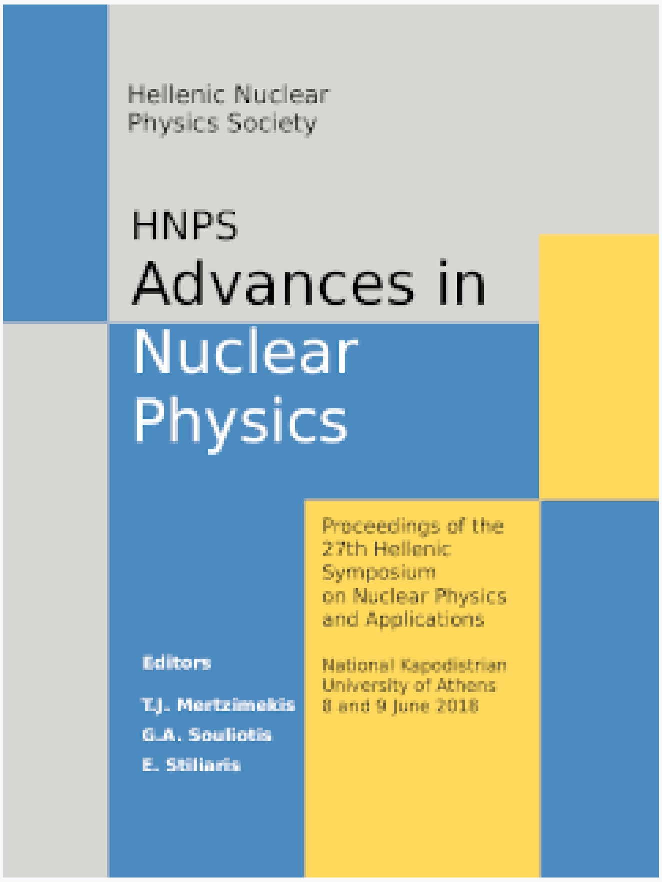
Annual Symposium of the Hellenic Nuclear Physics Society

Τόμ. 26 (2018)

HNPS2018



Neutron noise modelling for nuclear reactor diagnostics

A. Mylonakis, P. Vinai, C. Demaziére

doi: 10.12681/hnps.1809

Neutron noise modelling for nuclear reactor diagnostics

A. Mylonakis*, P. Vinai, C. Demazière

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

Abstract This paper presents the development of a neutron noise simulator for fine-mesh applications. The neutron noise of power nuclear reactors deals with the fluctuations of the neutron flux that are induced by fluctuations or oscillations of the reactor properties, i.e. displacement of core components, temperature or density variations, etc. Since the appearance of these perturbations can be problematic for the operation of nuclear reactors, it is desirable to be able to analyze their possible effects. The comparison between the modelling of such perturbations and possible measurements also gives the possibility to determine the driving perturbation in an operating nuclear reactor. One modelling approach is to solve numerically the neutron noise diffusion equation. This paper presents CORE SIM+, an under-development numerical tool oriented to neutron noise problems that require the fine-mesh spatial discretization of the reactor core.

Keywords reactor neutron noise, CORE SIM, GMRES, JFNK, ILU

INTRODUCTION

Neutron noise in power nuclear reactors consists of stationary fluctuations of the neutron flux that are induced by perturbations such as vibrations of reactor components, oscillations of coolant temperature or density, etc. Since these perturbations can be problematic for the operation of the nuclear reactors, their effects need to be analyzed. Therefore, computational capabilities have been developed to determine the transfer function of the reactor which describes the system response to any possible perturbation. The reactor transfer function can also be used for diagnostic purposes, i.e. to identify the neutron noise source from its effect on the neutron flux measured by the reactor instrumentation [1-3].

The modelling of reactor neutron noise should, as for the modelling of the static flux, rely on the neutron transport equation. Using this equation is nevertheless challenging for these kinds of problems because a nuclear reactor core is a very heterogeneous and large system. Then a typical, simplified approach for full reactor core neutron noise calculations is based on the diffusion approximation.

An example of diffusion neutron noise simulator is CORE SIM [4]. This tool solves the static neutron diffusion and the frequency-domain neutron noise diffusion equations discretized with a finite-difference scheme. Although CORE SIM as well as other diffusion codes have been successfully applied to the analysis of neutron noise problems, they have limitations due

* Corresponding author, email: antmyl@chalmers.se

to their numerical algorithms. In fact, most neutron noise sources are highly localized, so a very fine spatial discretization of the equations is necessary for an accurate prediction of the strong gradients of the neutron flux near the perturbation. The use of fine computational meshes leads to large systems of algebraic equations whose solution with direct methods, requires severe or even prohibitive computational burden in terms of computer memory and running time. The objective of the work is to present CORE SIM+, an under-development CORE SIM-based numerical tool oriented to fine-mesh 3-D full-core neutron noise problems.

The structure of the paper is as follows. The next section gives a brief description of the algorithms of CORE SIM+. Afterwards, a neutron noise simulation of a Pressurized Water Reactor (PWR) is presented in order to confirm the applicability of the tool to the target problems with a reasonable computational cost. Thereafter, some conclusions are drawn.

ALGORITHMS OF CORE SIM+

CORE SIM+ simulates neutron noise in two steps: first, it computes the steady-state neutron flux and second, it calculates the neutron noise in the frequency domain. One obtains the total space-dependent response of the reactor behavior by adding the neutron noise to the steady-state neutron flux.

To facilitate the modelling of highly localized perturbations, a non-uniform mesh capability is provided. This allows for the usage of a finer mesh in the areas of interest, e.g., close to the perturbation, and a coarser mesh in the remaining regions of the reactor core. In addition, the process of matrix construction has been optimized in order to reduce the computational time together with the utilization of computer memory.

The standard algorithm for solving the steady-state problem which is an eigenvalue problem, is the Power iteration or Power Method (PM) [5]. The main advantage of PM is that it guarantees the convergence to the eigenpair of interest and at the same time is very simple. However, the method is known to converge slowly when analyzes 3-D full-core problems, thus the implementation of an acceleration technique is important. The first acceleration technique that has been implemented in CORE SIM+ is the method of Chebyshev polynomials. This method updates the neutron flux estimate of a PM iteration as a linear combination of the solutions of some previous iterations. The determination of the linear combination coefficients is based on Chebyshev polynomials in order to minimize the error of the estimation. Various alternatives of the method can be used. The selected implementation is described in [6].

Additionally, a method of nonlinear acceleration based on the Jacobian Free Newton Krylov algorithm (JFNK) [7] has been implemented. JFNK being a generic Newton-based method allows seeking quadratic convergence rates. Various JFNK-based algorithms for the solution of reactor steady-state problems have been proposed. The version used in CORE SIM+ follows the work of [8]. This formulation aims to the acceleration of PM by its encapsulation into a Newton context without any modification. The approach retains the PM mechanism and thus it has the advantage to be easily adaptable to a PM solver. Second, it has been shown to exhibit higher performance than other Newton-based methods when applied to multigroup neutron diffusion problems [8].

The overall scheme requires the solution of the linear systems generated within PM and the linear system associated to the final calculation of the neutron noise in the frequency domain. These linear systems consist of sparse matrices which are also large if a fine mesh is used for the spatial discretization of the equations. Then iterative linear solvers are a more preferable choice since the storage requirements and the number of operations are less demanding in comparison to direct methods. On the other hand, they often converge slowly or even fail to converge, so preconditioning is necessary. CORE SIM+ uses the iterative Generalized Minimal RESidual (GMRES) method together with two preconditioners for the acceleration of convergence, i.e. Symmetric Gauss Seidel (SGS) and Incomplete LU with zero fill-in or ILU(0). Also, an option of loading an externally computed preconditioner is provided.

NUMERICAL RESULTS

As a proof of principle, a fine-mesh 3-D full-core neutron noise problem is simulated. This is a fully-heterogeneous PWR model where the noise source is a high-frequency localized absorber of variable strength, i.e., a perturbation in the thermal macroscopic absorption cross section with frequency of 1 kHz. In order to test the limits of the simulator, a fine uniform mesh is used instead of a non-uniform one. The node size is $\Delta x = 0.8958$ cm, $\Delta y = 0.8958$ cm, and $\Delta z = 7.62$ cm. Thus, a 384x384x52 Cartesian mesh is used leading to 11,261,952 unknowns; a problem that is unsolvable with CORE SIM. Fig. (1) illustrates the PWR core configuration together with the location of the perturbation.

The steady-state neutron flux along with the neutron multiplication factor are computed with PM accelerated with Chebyshev polynomials and GMRES preconditioned with ILU(0). The computation lasts 2.58 h utilizing no more than 10 Gb computer memory. This computation should be performed only once. Afterwards, multiple neutron noise simulations can be performed where the steady-state information is loaded by the noise solver as an input.

The neutron noise is calculated with GMRES preconditioned with ILU(0) using a tight convergence criterion (10^{-10}) of the relative linear residual. The computation lasts 43 min with utilization of no more than 10 Gb of computer memory. Fig. (2) illustrates the magnitude and Fig. (3) the phase of the predicted fast and thermal neutron noise. The gradients of the neutron noise are notable, confirming that the highly-localized neutron noise sources need fine spatial meshes. The fact that the neutron noise is localized around the point of the perturbation suggests that a coarse mesh with a refinement only in the surroundings of the perturbation could be sufficient to provide an accurate prediction and at the same time could reduce the computational effort.

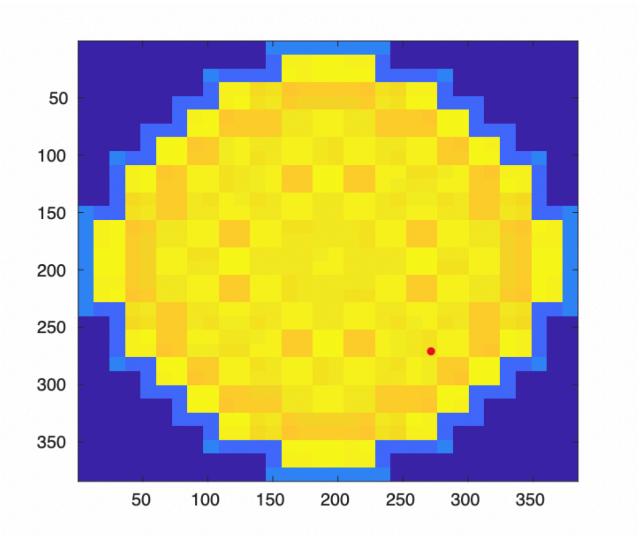


Fig. 1. PWR core configuration and location of the absorber of variable strength (red bullet)

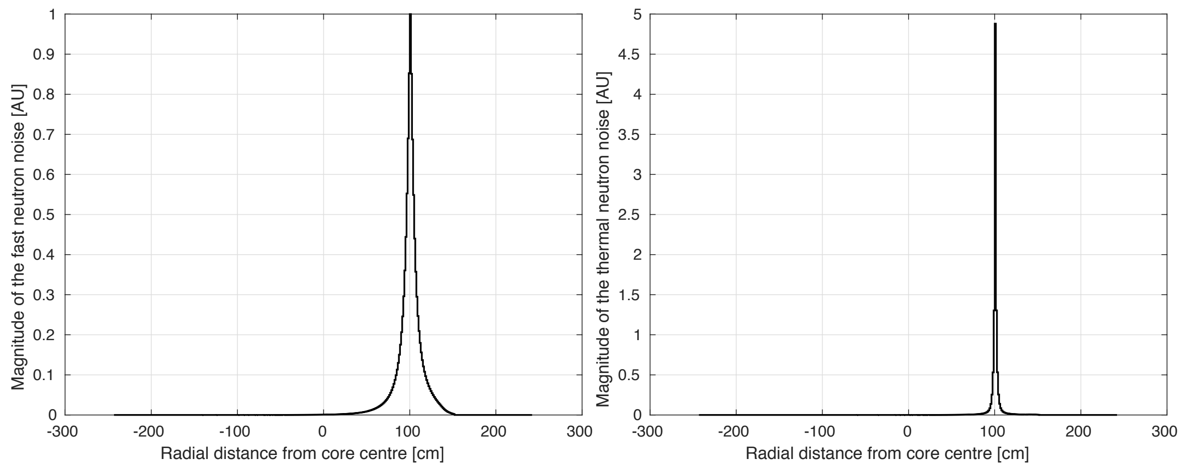


Fig. 2. Magnitude of the fast and thermal neutron noise

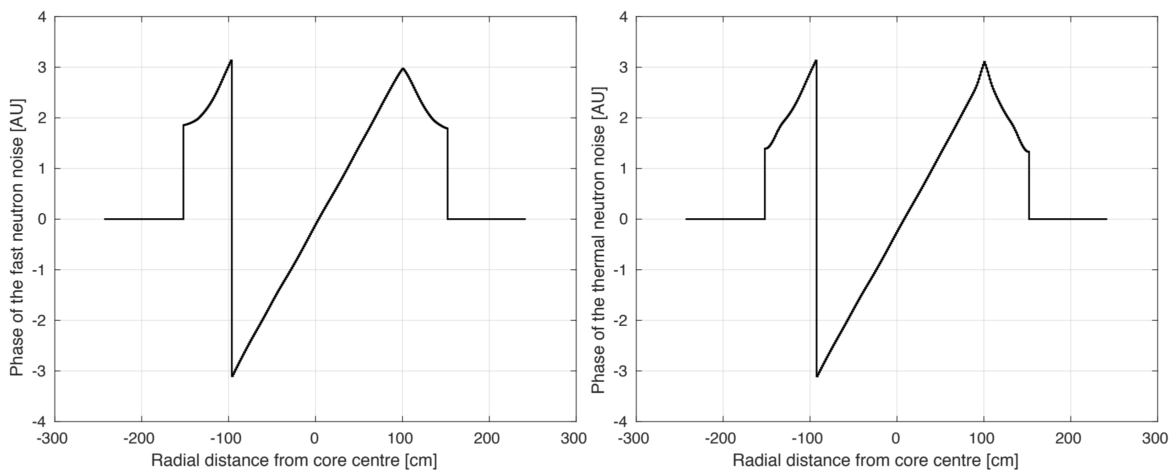


Fig. 3. Phase of the of the fast and thermal neutron noise

SUMMARY AND CONCLUSION

This paper presents CORE SIM+, an under-development numerical simulator oriented to neutron noise problems that require a fine-mesh spatial discretization of the reactor core. The tool provides a capability of non-uniform spatial mesh together with an optimized matrix construction process. The steady-state neutron flux is computed with the Power Method. Two methods are available for the acceleration of PM: the method of Chebyshev polynomials and a non-linear technique based on the Jacobian-Free Newton Krylov approach. For the solution of the linear systems, the GMRES method is used and assisted with a SGS or an ILU(0) preconditioner. To prove the applicability to the problems of interest, a high-frequency absorber of variable strength in a fully heterogeneous PWR whole-core was simulated. The tool was able to solve the problem with a reasonable computational effort.

Acknowledgment

The research leading to these results has received funding from the Euratom research and training program 2014-2018 under grant agreement No 754316.

References

[1] M. Williams, Random Processes in Nuclear Reactors, Pergamon Press, (1974)
[2] J. Thie, Power Reactor Noise, American Nuclear Society, (1981)
[3] C. Demaziere and I. Pazsit, Noise techniques in nuclear systems, Handbook of nuclear engineering, Springer, (2010)
[4] C. Demaziere, Ann. Nucl. Energy, 38: 2698-2718, (2011)
[5] E. Lewis and W. Miller, Computational methods of neutron transport. Jonh Wiley and sons, (1984).
[6] A. Hebert, Nucl. Sci. Eng., 91: 414-427, (1985)
[7] D. Knoll and D. Keys, J. Comput. Phys., 193: 357–397, (2004)
[8] D. Gill and Y. Asmy, A Jacobian-Free Newton-Krylov iterative scheme for criticality calculations based on the neutron diffusion equation. M&C2009, (2009)
[9] Y. Saad and M. Schultz, SIAM J. Sci. Stat. Comput., 7:856–869, (1986)