OPEN SOURCE NEUTRON NOISE MODELLING

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Chalmers University of Technology has been the leading university in the area of neutron noise and noise diagnostics since the 90s, when Prof. Imre Pázsit took the chair in reactor physics, bringing his expertise in this area. Neutron noise-based diagnostics aims at extracting information of possible anomalies existing in commercial nuclear reactors from the neutron noise measured by in-core and ex-core neutron detectors, the neutron noise being defined as the temporal variations of the neutron flux from its mean value, assuming that the system is stationary. The main advantage of noise analysis lies with the fact that the technique can be applied while the reactor is running at nominal conditions and without disturbing plant operation, thus providing the possibility to early detect anomalies and online.

Most noise diagnostic problems are equivalent to unfolding tasks, i.e., one needs to infer from usually very few neutron detectors the type of perturbation existing in the system, its features, and when relevant its position. This unfolding requires the prior determination of the reactor transfer function, i.e., the mathematical relationship existing between any spatial point $\mathbf{r}_0$ at which a perturbation might exist and the response of the system at any spatial point $\mathbf{r}$ to such perturbations. This relationship is given by the Green's function of the reactor.

As already pointed out in [1], being able to estimate the Green's function for heterogeneous systems would be advantageous. The development of computational methods in this respect was undertaken at Chalmers University of Technology in the early 2000s. This resulted in the official release of the CORE SIM tool in 2011 [2]. Since CORE SIM was the first tool of its kind, the simplicity of the use of the tool and the robustness of the numerical algorithms were key aspects considered when developing the tool.

CORE SIM is entirely developed in MATLAB, capitalizing on the numerical methods available within MATLAB. One of the main reasons for choosing MATLAB was the fact the estimation of the reactor transfer function is most easily performed in the frequency-domain, for which MATLAB native capabilities of handling complex arithmetic was clearly advantageous. The tool allows modelling in two-group diffusion theory three-dimensional heterogeneous systems in cartesian geometry and for one group of precursors of delayed neutrons. The spatial discretization of the equations is based on finite differences. The tool estimates both the static neutron flux and the first-order neutron noise in the frequency domain. The solver has the ability to model both critical systems and sub-critical systems driven by an external neutron source. The tool has also some extra capabilities of great advantage when studying reactor dynamics. In this respect, the tool estimates the adjoint functions of the reactor associated to both the static flux and the neutron noise. Moreover, the tool provides the different pairs of eigenvalues and eigenfunctions associated to the static problem. On the numerical side, two types of equations are solved by the tool: source problems and eigenvalue problems. The source problems are obtained when solving static subcritical configurations and any dynamical problem and are based on the MATLAB builtin LUPQ decomposition. The eigenvalue problems correspond to static critical configurations and are also encountered when the eigenvalues/eigenfunctions associated to a subcritical system are desired. The basic techniques implemented to solve such eigenvalue problems are based on the explicitly-restarted Arnoldi method and on the power iteration method with Wielandt's shift technique, the former being the default one. Such methods are coded in CORE SIM, making use of the LAPACK package available within MATLAB.

The simplicity of use of the tool was important when developing the tool. Using the tool does not require any input deck writing. A very short setting file allows changing the parameters in the various numerical methods. Keeping the default values is most often sufficient. It is only when convergence problems arise that the user needs to change those settings. All input data necessary to use the tool should be created by the user in a pre-defined format. Those data are sets of three-dimensional material data (macroscopic cross-sections and diffusion coefficients), as well as point-kinetic data if neutron noise calculations are to be performed. A uniform spatial mesh is used in the tool, for which the elementary size of a node needs to be defined. The tool is also provided with a Graphical User Interface (GUI) (illustrated in Fig. 1) that allows easily visualizing the input and output data for both the static and dynamic problems.

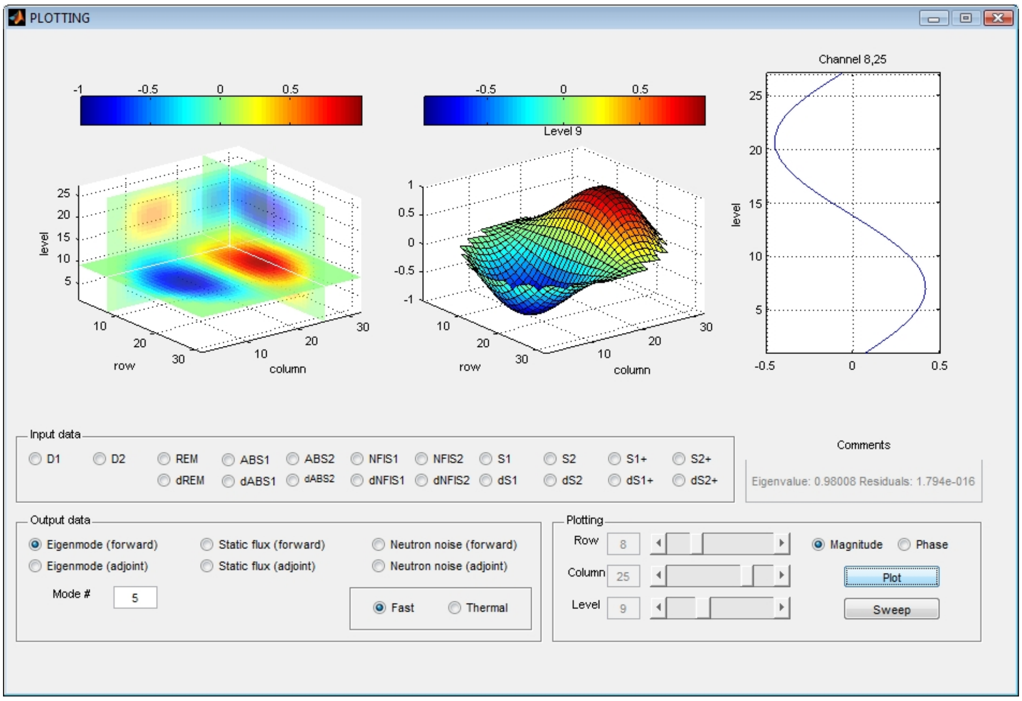

FIG. 1. Illustration of the CORE SIM GUI.

CORE SIM is available under the GNU General Public License. How to best make the tool available was discussed using support functions in the area of innovation and utilization at Chalmers University of Technology. Compliance with export control regulations was also checked. In order to increase the availability of the tool, it was deemed better not to make the tool available via any databank. A publication in Annals of Nuclear Energy describes the tool, its features, and illustrates some of the capabilities of the software. This publication also mentions the fact that the tool is freely available and can be directly requested from the author. When receiving any request, the requestor is asked to sign an agreement stating that one has to adhere to the GNU General Public License, that the tool is distributed without any warranty, that the requestor is not entitled to any dedicated technical support (even if the author of the program will help in the best of his availability), and that the tool cannot be used for any funded work/application without the prior consent of the requestee. Most importantly, the requestor promises to cite the original publication in any publication resulting from the use of the tool, either in its non-altered or altered form. The GNU General Public License also states that any modification of the software remains a free software.

After receiving the signed agreement from the requestor, the complete CORE SIM package is sent. It includes the source code, some examples, and most importantly, complete manuals. Those manuals are:

— A user's guide, detailing the code package, the file architecture, the necessary input data and their format, the output data and their format, how to use the tool, and finally the provided examples.
— A methodology manual describing all methods used in the code in depth and their implementation.
— A manual presenting all the verification cases associated to the tool.

The verification represented a very significant work that was important for demonstrating the correctness of the implementation of the models in CORE SIM, also considering the fact that the tool was the first of its kind. So far, the tool has been distributed to 39 users/organizations worldwide.

CORE SIM nevertheless requires the potential users to have access to MATLAB, which can limit the usability of the tool. Compiled versions of the tool on Windows operative systems were successfully tested and could also be distributed, if a requestor does not have access to MATLAB.

CORE SIM and its further developments were also used as the workhorse within the Horizon 2020 CORTEX project (CORe monitoring Techniques and EXperimental validation and demonstration) to generate, in the early phase of the project training, validation and test data sets for machine learning. The project, led by Chalmers University of Technology, gathers 19 European organizations, and 2 non-European organizations (from the US and Japan). It aims at developing a neutron noise-based core monitoring technique for which the unfolding is based on machine learning [3]. The Artificial Intelligence algorithms use a very large set of simulation data for postulated scenarios of anomalies. Using such data sets, the machine learning algorithms are capable of identifying, from actual neutron noise measurements at operating nuclear reactors, the perturbations suspected to exist at those reactors. During the CORTEX project, an extended version of CORE SIM, called CORE SIM+, has also been developed [4]. The main improvement lies with fine mesh capabilities that required to implement other numerical techniques. CORE SIM+ will soon be officially released. When CORE SIM+ became available within the project, all neutron noise simulations in the frequency-domain and for the western-type Pressurized Water Reactors considered in the CORTEX project were carried out with CORE SIM+ instead of CORE SIM.

Due to the free availability of CORE SIM and its transparent documentation, many organizations undertook the development of similar neutron noise capabilities using either transport or diffusion, the time-domain or the frequency-domain, based on either deterministic approaches or Monte Carlo techniques. Detailing all the tools CORE SIM inspired is beyond the scope of this paper. Some benchmark cases between CORE SIM or

CORE SIM+ with some of those other codes were also successfully carried out, both as part of CORTEX and outside of it.

In conclusion, the free availability of the CORE SIM package together with all its manuals and the extensive verification of the software were key for demonstrating the usefulness of the tool and the correctness of the estimated numerical solutions. When developing CORE SIM, emphasis was put on the robustness of the tool and on fast running calculations. Those two aspects were essential for the CORTEX project, for which very large sets of simulation data had to be generated. By making the tool freely available, many collaborations were initiated, most of them within CORTEX. CORE SIM is also being used in many small-scale projects internally at Chalmers University of Technology for investigating specific research questions or developing noise capabilities for advanced reactors. Another by-product worth mentioning of open-source software is the fact that making a tool freely available should be accompanied by a publication to be referred to. The use of the tool or derivations from the tool by others will thus result in many citations of the publication, which is an important aspect to consider in academia.

REFERENCES

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