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Developing and investigating a pure Monte-Carlo module for transient neutron transport analysis

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ABSTRACT

In the field of computational reactor physics, Monte-Carlo methodology is extensively used in the analysis of static problems while the transient behavior of the reactor core is mostly analyzed using deterministic algorithms. However, deterministic algorithms make use of various approximations mainly in the geometric and energetic domain that may induce inaccuracy. Therefore, Monte-Carlo methodology which generally does not require significant approximations seems to be an attractive candidate tool for the analysis of transient phenomena. One of the most important constraints towards this direction is the significant computational cost; however since nowadays the available computational resources are continuously increasing, the potential use of the Monte-Carlo methodology in the field of reactor core transient analysis seems feasible. So far, very few attempts to employ Monte-Carlo methodology to transient analysis have been reported. Even more, most of those few attempts make use of several approximations, showing the existence of an "open" research field of great interest. It is obvious that comparing to static Monte-Carlo, a straight-forward physical treatment of a transient problem requires the temporal evolution of the simulated neutrons; but this is not adequate. In order to be able to properly analyze transient reactor core phenomena, the proper simulation of delayed neutrons together with other essential extensions and modifications is necessary. This work is actually the first step towards the development of a tool that could serve as a platform for research and development on this interesting but also quite challenging field. More specifically, in this work, a capability for transient neutronic analysis has been introduced in the open-source Monte Carlo code OpenMC. The selected methodology that has been proposed recently by other researchers is inserted in OpenMC following its own features, trying to minimize the necessary modifications and to maximize the advantage by its existing capabilities. The key points of the module which is under development, as well as the results of the analysis of preliminary numerical experiments are presented and discussed. The obtained results are encouraging and very promising in terms of accuracy, giving motivation for further investigation and development.

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1. Introduction

Nowadays, computational nuclear reactor analysis is moving towards integrated and detailed analysis of the system "reactor core" in a multi-physics context (Zerkak et al., 2015; Mylonakis et al., 2014a). In this framework, static Monte-Carlo analysis is extensively employed standalone and/or coupled with other tools (Vazquez et al., 2012; Leppanen et al., 2012; Mylonakis et al., 2014b; Daeubler et al., 2015; Mylonakis et al., 2015), since it can provide thorough description and analysis of the neutronic model of the reactor. At this point a scientific "gap" arises; while transient phenomena (normal or accidental) are of great interest, the Monte-Carlo methodology that could analyze them without making use of significant approximations is not extensively employed in this domain. As transient analysis is an important issue concerning the reactor safety and design, various techniques, mainly deterministic or hybrid (i.e. deterministic/Monte-Carlo), are employed. However, common feature of almost all of them is that they make use of various approximations and they are strongly

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problem-dependent. As regards deterministic methods, point kinetics is the most common and simple method to perform transient analysis, however, having adopted inherently significant approximations. In addition, a variety of space- and time-dependent deterministic methods have been developed and utilized including however approximations that concern mostly the discretization of space, time, angle and energy. On the other hand, Monte-Carlo kinetic analysis of hybrid nature has been achieved coupling the Monte-Carlo methodology for the calculation of the static neutron flux distribution with simplified treatment of the temporal evolution, called quasi-static approximation (Dulla et al., 2008; Goluoglu et al., 1998). The almost inexistence of pure Monte-Carlo dynamic tools that inherently do not need significant approximations, reveals the existence of an "open" research field of great interest. Recently, a methodology that analyzes in a pure Monte-Carlo way the physical phenomena that are involved in the transient behavior of a reactor core has been published in Sjenitzer (2013), Sjenitzer and Hoogenboom (2013), Legrady and Hoogenboom (2008) and Sjenitzer and Hoogenboom (2011) and constitutes the starting point for this work. Of course the main constraint of performing large scale Monte-Carlo simulations is the prohibitive computational cost as mentioned, for example, in Martin (2012). This argument is stronger when time-dependent problems are considered. However according to Martin (2012), when speaking for static analysis, literature results show that Monte-Carlo simulation is moving towards finer and finer resolution within more and more realistic computational cost. The results presented in Sjenitzer (2013) indicate that this conclusion might be considered representative also for the field of Monte-Carlo transient analysis.

General motivation for this work is the great interest for the development of a pure Monte-Carlo tool able to perform transient analysis without making significant approximations. The main aim of the present work, is to present a module for transient analysis that is currently under development using as basis the open-source Monte-Carlo transport code OpenMC, as well as to show preliminary results and to present the next steps of the development procedure.

2. Aim of this work

Interest of the authors is to develop and investigate a pure Monte-Carlo numerical tool able to analyze the kinetic neutronic behavior of a nuclear system. Comparing to the steady-state form of the existing Monte-Carlo algorithms it is clear that a way should be found in order to encapsulate the impact of precursors as source of delayed neutrons in the corresponding time scale, in order to analyze properly the temporal evolution of the transient phenomenon. However it is obvious that the main constraint towards this direction will be the necessary simultaneous treatment of phenomena of different time-scales that are involved in this physical process which, in a stochastic context, will induce variance in the statistical estimation of the desired quantities. A promising technique that tries to alleviate this problem has been presented in Sjenitzer (2013) and is the basis of the way that delayed neutrons are treated in this work. In addition various other needs of such a scheme, comparing to existing Monte-Carlo static algorithms, are treated in order to achieve the desired goal. It should be noted that in this development stage some approximations, that are described below, are used since they can limitate the number of factors that could complicate the validation process and in the same time they are considered reasonable for the simplified problems that analyzed here.

3. The transient module

3.1. The OpenMC code as host for developing the transient module

OpenMC (Romano and Forget, 2013) is a new, open source, Monte-Carlo transport code written in modern Fortran programming language. It provides the capability for *k*-eigenvalue (criticality) and fixed-source analysis. The principal reason that this code has been selected for the research and development procedure within this work, is that it is open-source and therefore it can facilitate the developing procedure without any constraint. The fact that it is written in modern Fortran making use of "type" structures and other modern programming features is another reason that makes OpenMC an attractive host. In addition, it is characterized by some other important features such as a very effective parallelism pattern that allows excellent scalability up to some hundreds thousands processors for even *k*-eigenvalue calculations (Romano and Forget, 2013). Furthermore, its input files are written in XML (Extensible Markup Language) format rather than the arbitrary code-dependent text formats which are used by the majority of codes, simplifying significantly the development of models.

3.2. General description of the transient module

In this paragraph the generic flowchart of the developed computational scheme is described. Since a transient phenomenon usually follows, somehow, the perturbation of the reactor core steady-state, an initial static criticality calculation is performed in order to create the critical neutron source from which the transient particle source will be generated. Using this neutron source, a prompt and a precursor source distribution is generated, utilizing the proper analogy between them. When the source is ready, the simulation starts. At the beginning of each time-step the decay process of precursors is simulated. It should be noted that according to Sjenitzer (2013), each precursor is forced to produce a delayed neutron within each time-step without dying afterwards, for reasons that will be explained below. Within each time step the neutrons coming from the previous step and the ones generated by the precursor decay at the beginning as well as within the current time-step, are simulated. The simulation within each time-step is done in a generation-by-generation context. During a time-step a fission event may generate prompt and delayed neutrons. If a delayed neutron is going to be produced, a precursor is firstly generated and saved in the proper bank and then its decay process is simulated. This results in a forced birth of a delayed neutron within the remaining time interval of the current time-step. If a neutron crosses the time boundary of the current time-step, it is stored and its simulation continues in the next step.

The development of this new module was based on the fixed-source scheme of OpenMC following the general flowchart of that module; as a result the simulation of the whole phenomenon is performed in each batch. Since OpenMC calculates statistics considering each batch as a single realization of the random variable, the selected approach is compatible and can take advantage of the already existing tallying capabilities which are extended in this work in order to provide the necessary monitoring in time. In order to be able to apply changes that could initiate a transient such as the movement of a control rod or the change in the density of a material, a suitable subroutine has been developed. This subroutine gives the ability to define a variety of dynamic changes by properly combining the construction of the geometry/materials input and the definition of the dynamic change. Another modification is the extension of the existing structured mesh adding an extra dimension in order to be able to track the desired quantities in time. As a result, each tallied quantity can be calculated in the

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