Annals of Nuclear Energy 101 (2017) 226–236

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

SFR mechanical scenarios and neutron transport transients with CAST3M code

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A R T I C L E I N F O

Article history:
Received 1 April 2016
Received in revised form 4 November 2016
Accepted 13 November 2016
Available online 19 November 2016

Keywords:
Sodium Fast Reactor
Mechanical vibrations
Transient
Cast3M
Diffusion code
Fluid-Structure Interaction

A B S T R A C T

In this paper we focus on of Sodium Fast Reactor core undergoing several mechanical scenarios. The mechanical full-core model in Cast3M code is described using finite elements method and Fluid-Structure Interaction is taken into account. We consider several system excitations: fluid injection, seismic excitation and compressive/opening forces applied to the bundle of assemblies. The geometry deformation is next applied for transient neutron transport simulations using a diffusion tool built in Cast3M code, named Cast3M Neutron Transport Tool (CNTT). We expose and analyze variation of power, change of fissile zone volume and assembly displacements. CNTT succeeded in code-to-code comparison using TRIPOLI-4 (a Monte Carlo code) and APOLLO3 (a deterministic code). The novelty of CNTT is the use of remeshing to take into account core distortion. The validity of assumptions applied in our approach and prospects for the future are discussed as well. The developed methodology may serve as a general tool for analysis of fast reactor systems under various mechanical excitation. Cast3M based tools provide new possibilities for safety assessments, fundamental for current and upcoming nuclear designs.

1. Introduction

Among the concepts of nuclear reactor systems postulated on the Generation IV International Forum (GIF, The Generation IV International Forum), Sodium Fast Reactor (SFR) option has been intensively studied in recent years in CEA (Atomic Energy and Alternative Energies Commission, France). Multi-physics codes are constantly being developed, tested, validated and applied to provide better understanding of core behavior. Concerning the safety assessments, representative transient simulations are of special interest.

A lot of SFR safety studies have already been performed, for example: estimation of reactivity coefficients (Zhang and Mikityuk, 2016), different perturbations of coolant flow (Schikorr et al., 2015) (Kruessmann et al., 2015), scenarios of control rods insertion/withdrawal (Devan et al., 2012; Rajan Babu et al., 2014) and fuel performance under abnormal conditions (Papin, 2012). The coupling between neutronic, thermal-hydraulic and thermal-mechanical codes are applied by authors Fiorina et al. (2015), Clarno et al. (2012). General methodology for large scale mechanic-neutronic transient has not been established so far. Doctoral thesis by Gottfridsson (2011) presents a review of research on this topic in the context of Phenix reactor. The studies concerning neutron noise induced by periodic core deformations have been recently done by Zylbersztejn et al. (2014). New methodology gives insight into particle flux response in energy and space domain for imposed periodic flowering of system. This research is complementary to ours as we focus on more general core excitations while keeping neutron transport model reliable.

The development of tools dedicated for SFR systems analysis progresses in CEA. The papers by Broc and Sigrist (2010), Broc et al. (2014, 2015) describe recent advances in modeling of core mechanics with the Cast3M code (Le Fichoux, 2011). The work by Patricot et al. (2014) demonstrates the topic of deterministic neutron transport simulations in deformed geometry. The paper by Patricot et al. (2016) show a development of other approach. The current article presents a first study combining mentioned methodologies and demonstrates feasibility and usefulness of this

Abbreviations: SFR, Sodium Fast Reactor; CFSI, Cast3M Fluid-Structure Interaction (tool); CNTT, Cast3M Neutron Transport Tool; CEA, Atomic Energy and Alternative Energies Commission; FSI, Fluid-Structure Interaction; FEM, Finite Element Method; LNP, Lateral Neutron Protection; FA, Fuel Assembly; CR, Control Rod; EOL, End-of-Life.

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http://dx.doi.org/10.1016/j.anucene.2016.11.016
0306-4549/

multi-physics approach in application to whole-core model. We create a general tool for modeling SFR transients initiated by mechanical excitations.

In this paper we present a methodology for transient simulation of SFR. We model several mechanical scenarios with Cast3M to obtain time-dependent spatial displacements of assemblies. We describe the system using Finite Elements Method. The Fluid Structure Interaction (FSI) is taken into account though an homogenization technique which provides acceptable computational cost for whole core simulations. Considered scenarios comprise: fluid injection, seismic excitation, compressive/opening forces applied to core bundle and control rods insertion. Geometric deformations are applied in the neutronic part analyzed with Cast3M Neutron Transport Tool (CNTT). This diffusion code performs critical and transient simulations in Cast3M mesh as shown by Patricot et al. (2016). We confirmed the validity of CNTT responses to geometry deformation using TRIPOLI-4 (Brun et al., 2015) and APOLLO3 (Golfier et al., 2009) codes. We consider one-way coupling – the feedback from neutron transport to mechanical calculation is neglected (and negligible).

The novelty of our approach concerns is the direct solving of discretized time-dependent neutron diffusion equation on deformed mesh (presented by Fiorina et al. (2014), Fiorina and Mikityuk (2015)), which differs from the pixelation strategy applied by Patricot et al. (2014). Our new methodology gives an alternative way for modeling of neutron transport transients. Numerical model is not limited to hexagonal geometry or specific type of reactor.

First, we present the methodology used in our research: CFSI (Section 2) and CNTT (Section 3). Section 4 shows the models and explains the assumptions. In Section 5 the validation of CNTT is presented (code-to-code comparison). Mechanical scenarios are explained in Section 6. We show the results in Section 7. The prospects are given in Section 8. The summary and our conclusions are presented in Section 9.

2. Cast3M Fluid-Structure Interaction (CFSI)

Cast3M is a computer code for the analysis of structures by the finite elements method (FEM) and the Computational Fluids Dynamics (CFD) as explained in Le Fichoux (2011). The numerical methodology available in the Cast3M toolbox helped to prepare Cast3M Fluid-Structure Interaction (CFSI) tool actively applied in our study.

In our modeling, the core is treated as a hexagonal bundle of beams (each beam represents an assembly) located on a stiff diagrid. The collisions between the assemblies are accounted at the levels of spacing pads (plates limiting core compression) and at the top of bundle using so called impact stiffness, so a direct interaction between solid structures is modeled. The visualization of hexagonal core bundle and collision sites is shown in Fig. 1. Reliable prediction of core behavior under time-dependent mechanical excitation requires also modeling of its interaction with fluid.

Inter-wrapper liquid sodium surrounding assemblies significantly modifies their movements. It has been proved far enough that even for relatively small displacements, the inertia effects of fluid meaningfully decrease the frequencies of structure vibrations (as shown by Broc et al. (2014, 2015)). Thus the physical behavior of the liquid needs to be modeled in Cast3M. So called Fluid-Structure Interaction phenomena are taken into account by Navier-Stokes equations for the fluid. Dimensional analysis of these equations leads to conclusion that for little displacements the turbulent term can be neglected. Because current study deals with little displacements of structures, simpler Euler linear equations can be used instead (presented by broc and Sigrist (2010)).

If we describe fluid motion by the linear equations, homogenization method can be applied (derived and presented by Sigrist and Broc (2009), Broc and Sigrist (2010), Broc et al. (2014)). We define an elementary cell (tube immersed in fluid) with 2 degrees of freedom: acceleration of tube and mean acceleration of liquid. The cell and the result of homogenization are shown in Fig 2.

Numerical equations can be derived on the basis of the so called (X_S, P, φ) formulation (structure displacement, fluid pressure, potential displacement) as shown in the work by Broc and Sigrist (2010). We account for damping of structure vibrations using so called Rayleigh damping approach.

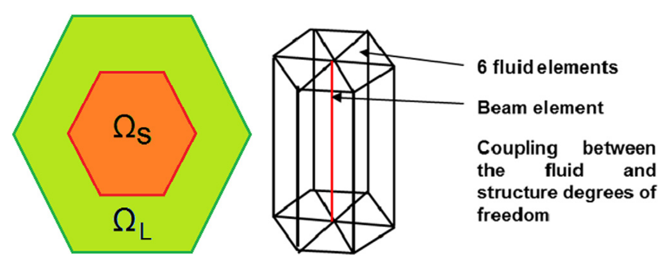

Fig. 2. Left: elementary cell for the homogenization in the system (solid S surrounded by liquid L). Right: scheme of the finite element (as given in (1)).

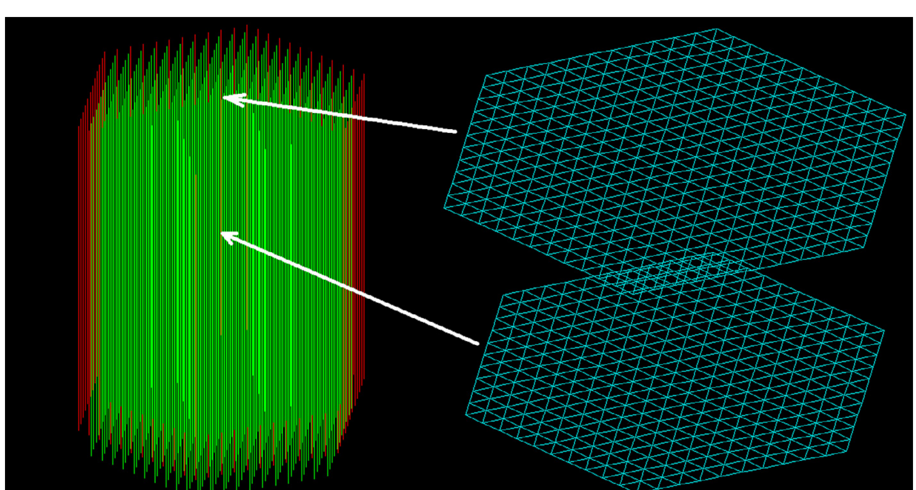

Fig. 1. Left: bundle of beams representing core model (green –internal core, red – Lateral Neutron Protection). Right: collision sites for the model of impact stiffness. Arrows indicate location in the system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)