MODELLING AND ANALYSIS OF FUEL ASSEMBLY VIBRATIONAL MODES IN PWRs USING SIMULATE-3K

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ABSTRACT

Some of the KWU pre-KONVOI PWRs operating across Europe saw a systematic increase in the neutron noise levels over several cycles in the last decade, and subsequently, core internals' movements, especially vibrations of fuel assemblies with specific designs were identified as one of the plausible causes. Therefore, it is important to develop computational methods that can allow to investigate and predict the reactor noise response to fuel assemblies vibrations. To this aim, the 3D nodal reactor dynamics code SIMULATE-3K is used at PSI with a special module called the 'assembly vibration model' that imitates time-dependent motions of fuel assemblies by dynamically modifying the water-gaps surrounding the laterally moving fuel assemblies. The varying water-gaps are represented by the variation in the corresponding two-group macroscopic cross sections generated using the lattice code CASMO-5 in 2D. The studies conducted so far to assess the methodology for full core noise simulations were based on assuming vibrations of a clamped-free cluster of fuel assemblies that are unsupported from both ends. However, as this represents a non-physical movement, further developments were made at PSI to allow simulating more realistic movements of fuel assemblies such as the cantilevered mode vibration. The updated methodology, along with evaluations of the simulated noise response to realistic vibration modes, is presented in this paper. Results show that, as expected, the radial and axial neutron noise behaviour follow the vibration pattern of the imposed time-dependent axial functions corresponding to the natural oscillation modes of the fuel assemblies, thereby providing confidence in the application of the developed methodology for numerical neutron noise analyses of the PWR cores.

KEYWORDS: Neutron noise, fuel assembly vibrations, time-domain, CASMO-5, SIMULATE-3K

1. INTRODUCTION

The term noise refers to the deviation of any time-dependent quantity from its mean value. In a nuclear system, a fluctuation reflecting the inherent stochastic nature of neutrons, which is measured as a detector signal is regarded as neutron noise. In a nuclear reactor, several sources, including neutronic parameters, thermal-hydraulic perturbations like coolant flow blockage, inlet coolant temperatures or excessive vibrations of reactor core internals are responsible for the neutron noise.

Contrary to what the name suggests, analysis of such fluctuations in the neutron population in a reactor core is a rather useful and commonly used technique in reactor surveillance, where it is impractical to install wide range of diagnostic instrumentation without disturbing normal operations [1].

The CORTEX project (CORe monitoring Techniques and EXperimental validation and demonstration), which is funded by the European Commission, aims at developing core monitoring techniques that are capable of detecting, identifying and localizing anomalies in power reactors [2]. The motivation for the project originates from the partially unexplained neutron noise level increase observed in a certain type of PWRs operating across Europe. Over the last decade, some of the KWU pre-KONVOI PWRs in Spain, Germany and Switzerland have seen a systematic increase in the neutron noise levels over several cycles [3]. The unexpected increase in the neutron noise levels has had an impact on the availability of the plants, thereby, forcing the reactors to operate at reduced power. The increased neutron noise levels coincided with the introduction of a new fuel assembly (FA) type in the core, which presented vibration issues after undergoing several cycles of irradiation. Consequently, excessive mechanical vibrations of the structural components, specifically FAs with specific designs were recognised as one of the possible causes for the unexpected increase in the noise levels [4]. From an industrial perspective, it is, therefore, important to gauge the sensitivity of such perturbation initiators so that realistic alert levels can be determined and a continued reactor operation can be ensured.

Within the CORTEX project, methods for modelling of FA vibrations in time- and/or frequency-domain are currently under-development by various partners. The methods utilize existing state-of-the-art time-domain codes such as SIMULATE-3K (S3K), DYN3D, and APOLLO3 [5–8], and several in-house frequency-domain tools developed particularly for neutron noise analysis such as CORE SIM [9]. These codes express in-core perturbations as either fluctuations of macroscopic cross sections, or in more physical terms, as time-dependent vibrations of FAs due to fluid-structure interactions.

At the Paul Scherrer Institut (PSI), the methodology under development for numerical noise simulations is currently based on the time-domain approach and primarily targeted towards applications for the Swiss PWRs. The methodology consists of the in-house CMSYS platform, where reference steady-state core models based on the CASMO/SIMULATE code system are continuously developed and validated for all Swiss operating reactors and cycles [10], coupled with the S3K, a 3D multi-physics core dynamics solver along with its "assembly vibration model". To apply S3K with the assembly vibration model, an in-house MATLAB script was developed to imitate time-dependent lateral movements of chosen FAs in x- and/or y-directions by dynamically modifying the water-gaps surrounding the oscillating FAs. The MATLAB script was developed and used to define the water-gap widths around the oscillating FAs at each time step, and impose various vibrational patterns. This script was developed to complement the 'delta-gap model' in the lattice 2D code CASMO-5 [6,7], where two-group macroscopic cross sections are/were generated for water-gap variation representative of only static FA displacement. One of the previous studies assessed the impact from bowing in vibrating FAs on the induced neutron noise levels using the in-built fixed bow shapes in the 'assembly bow model' of SIMULATE-3 (S3) [11]. Another work performed a systematic verification of the CASMO/SIMULATE codes for the FA lateral displacements, both at the lattice and the assembly level. In addition, the effect of water-gap widths on the homogenised cross sections was verified by comparing CASMO-5 and SEPRPENT-2 results

[12]. However, these studies were limited to the modelling of vibrations of one or more clamped-free FAs, unsupported from both ends. Whereas in reality, FAs are typically clamped to the core support plates, thereby modifying the character of the FA motion. Therefore, recently, further developments have been carried out in the PSI neutron noise methodology to allow for modelling of more realistic movements of the FAs. The modifications are discussed in this paper where attempts to model realistic movements of the FAs and evaluate the core neutron noise response are presented. Out of the several possible modes of the FAs' vibration, the most significant ones are modelled here. These are the cantilevered mode (clamped-free at the top), and the C-shaped and the S-shaped mode (both simply supported from top and bottom and combined with cantilevered mode) [1]. A combined vibration with the cantilevered mode introduces larger displacement at the core-top than the core-bottom to ensure that the fuel assembly is better fixed at the bottom than the top. The detailed calculation methodology, including description of the core design, tools and the approach used to model FA vibrations using CASMO-5 and S3K, are given in Section 2. The calculation results are discussed in Section 3, followed by the conclusions in Section 4.

2. CALCULATION METHODOLOGY

A description of the modelling approach along with the tools used for the neutron noise analysis is given here. A typical four-loop Westinghouse mixed core PWR of the OECD/NEA transient benchmark is used for the study [13].

2.1. Calculation Codes

Within the CMSYS system, CASMO-5 is a multi-group two-dimensional lattice code for modelling light water reactor fuel, where the transport solution is based upon the Method of Characteristics (MOC). CASMO-5 generates multi-group cross section and discontinuity factor data, which is fed into downstream codes S3 and S3K using the CMS-LINK5 code for full core calculations. S3 is a three-dimensional, multi-group nodal code for the analysis of light water reactor cores. It performs steady-state core-follow calculations. S3K is a two-group nodal code for transient analysis of light water reactors. S3K performs coupled neutronic and thermal-hydraulic analysis, and is a preferred code of choice for several transient applications world over.

2.2. Modelling approach

The modelling of the FA vibrations within the PSI neutron noise methodology involves three main steps. First, CASMO-5 is employed to generate two-group homogenised macroscopic cross sections accommodating for the varying water-gap widths using the 'delta-gap model'. In addition to the default automated case matrix capability for generating nuclear cross section data, CASMO-5 performs another delta-gap branch calculation. This allows to modify the water-gap widths on any side of the oscillating FA, and generates macroscopic cross sections and discontinuity factors for the downstream S3 and S3K codes for full-core calculations. The model also takes assembly symmetry into account while generating the nuclear data. Note that it is assumed that the lateral vibration of a FA resembles an increase in the water-gap in one direction and a decrease by the same amount in the opposite direction. CASMO-5 does not perform an added branch calculation for the generation of cross sections corresponding to negative delta-gap widths for PWR FAs.

Second, every FA is equally discretized into Z axial nodes, and every node can be further divided into *2x2* planar sub-nodes. The cross sections from CASMO-5 are homogenised within each node. S3 solves the two-group three-dimensional diffusion equation for every node, and produces restart files for the transient code S3K, corresponding to the operating conditions of interest.

Third, the transient nodal code S3K is used to imitate realistic time-dependent movements of the FAs. As introduced earlier, S3K, consisting of the assembly vibration model, allows to simulate time-dependent movements of FAs in x- or/and y-direction by dynamically modifying the water-gap widths between any two FAs. To this aim, for a given direction of vibration, an in-house MATLAB script creates a user input file containing water-gap widths between the selected vibrating FAs at every time step. The script allows the user to impose water-gap widths maps in order to model flexible vibrational pattern in terms of choice of vibrating assemblies and vibration characteristics such as amplitude, phase and frequency, etc. The modification of the gaps between two neighbouring FAs due to the vibration of a central FA is represented by introducing pre-calculated CASMO-5 cross sections corresponding to the modified water-gap width of $\delta/2$ in eight affected sub-nodes. A schematic diagram is shown in Figure 1 to illustrate the modelling of lateral movement of a central assembly, FA_i, to the left direction. Modified cross sections, $XS_{+\delta/2}$, corresponding to an increased water-gap width of $\delta/2$ are introduced in the four sub-nodes, two each belonging to the oscillating assembly FA_i and the first neighbour, FA_{i+1}, on the right. Likewise, cross sections, $XS_{-\delta/2}$, corresponding to a decreased water-gap width of $\delta/2$ are introduced in the four sub-nodes belonging to FA_i and FA_{i-1}. This is done to conserve the fixed computational mesh in the core. The missing cross sections corresponding to negative delta-gap widths in pre-calculated CASMO-5 nuclear data are obtained with S3K by extrapolating the values to delta-gap width of -δ.
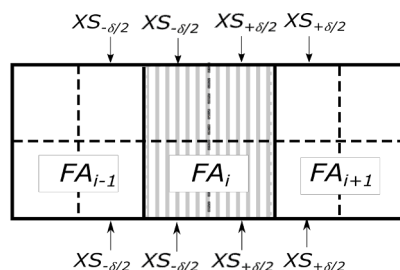

Figure 1: Modification of cross-sections when central assembly, FA_i, (striped) moves to the left direction. The modified cross sections, $XS_{-\delta/2}$ and $XS_{+\delta/2}$, introduced in the eight affected sub-nodes are marked.

Extending the development of the PSI methodology for modelling of FA vibrations, a beta version of the S3K code is used in this work, which includes a module that enables the user to impose pre-defined functions representative of the vibration modes of the FAs by assigning factored co-efficients between zero and one to each axial node. In other words, the FA is modelled to vibrate in a certain pattern by displacing each of the axial nodes by a width, δ that is calculated using these coefficients and the water-gap widths at every time-step. This enables S3K to replicate time-dependent complex movements of the FAs, and faithfully represent the associated neutron noise source in the core.

2.3. Calculation parameters

The central FA and the *5x5* central FA cluster are modelled separately to vibrate sinusoidally along the x-direction with a maximum displacement amplitude of 0.1 cm. The FA vibrations are performed at 1.2 Hz for the cantilevered mode and the C-shaped mode and 5 Hz for the S-shaped mode [1]. These frequencies correspond to the typical measured FA vibration frequencies, and the displacement amplitude is the typical half-distance between adjacent FAs in a KWU pre-KONVOI reactor. The simulation is performed for a duration of 35 s at a time step of 0.01s. The neutron fluxes in both fast and thermal groups are obtained with S3K at every node of the PWR core, comprising of *15x15* FAs and axially discretised into 32 nodes. The neutron noise is evaluated in terms of variation of neutron flux in the core using the statistical quatity, the coeffecent of variation (CV). CV, expressed as percentage, is defined as the ratio of standard deviation, s, to the mean value, $\overline{\mu}$, of the neutron flux, ϕ, in the energy group, G, obtained at any given node located at *i,j,k* in the core. It is expressed as,

$$CV_G^{i,j,k} = 100 \cdot \frac{s_{\phi_G^{i,j,k}}}{\overline{\mu}_{\phi_G^{i,j,k}}} \qquad (1)$$

3. RESULTS AND DISCUSSION

In this section, the results for the FA modelling of higher vibrational modes, and the corresponding induced neutron noise due to the vibration of the central FA and the 5x5 central cluster, are reported. The neutron noise behaviour is consistent across both fast and thermal energy groups. Only thermal neutron noise is shown here as the dynamic variation of water-gap widths due to the introduction of time-dependent oscillation of FAs affect the thermal neutron noise the most. The three vibrational modes evaluated are the cantilevered beam, the C-shaped and the S-shaped modes, shown alongside the corresponding axial noise profiles obtained with S3K in Figure 2(a), (b) and (c), respectively. The pre-defined axial neutron noise sources representative of the vibration modes are reflected in the neutron noise behaviour. The cantilevered beam mode, which is clamped-free at the top, introduces as expected, larger water-gap width around the vibrating assembly at the top compared to the bottom, and therefore, higher neutron noise amplitude is obtained at the top of the assembly. For instance, the maximum thermal noise amplitude at the top of the neighbouring assembly is 0.90% compared to 0.06% at the bottom for a centrally vibrating FA. In case of the C-shaped mode, the assembly offers some resistance to motion on both the ends, and introduces wider water-gap widths in the middle, which is reflected in the induced noise. The maximum thermal noise amplitude is 0.80% in the middle compared to 0.05% at the top and the bottom of the centrally vibrating assembly. In case of the S-shaped mode, the time-dependent vibration of the FA is seen where the neutron noise is split into two halves axially, with the maximum thermal noise amplitude of 0.79%. In addition, as expected, higher noise amplitudes are seen in case of the *5x5* cluster of FA vibrations compared to a single FA vibration, where the maximum noise amplitude reaches 2.54%, 2.24%, and 2.03% for the cantilevered, C-shaped and S-shaped modes, respectively. Figure 2(d) shows a comparison of the axial noise distribution along the neighbouring FA when a central *5x5* cluster of FAs is vibrated along the x-direction in the three modes. A tilt in the neutron noise amplitude is visible at the top compared to the bottom of the assembly for the C-shaped and S-shapes modes of vibration. This is due to the decreased coolant density in the core
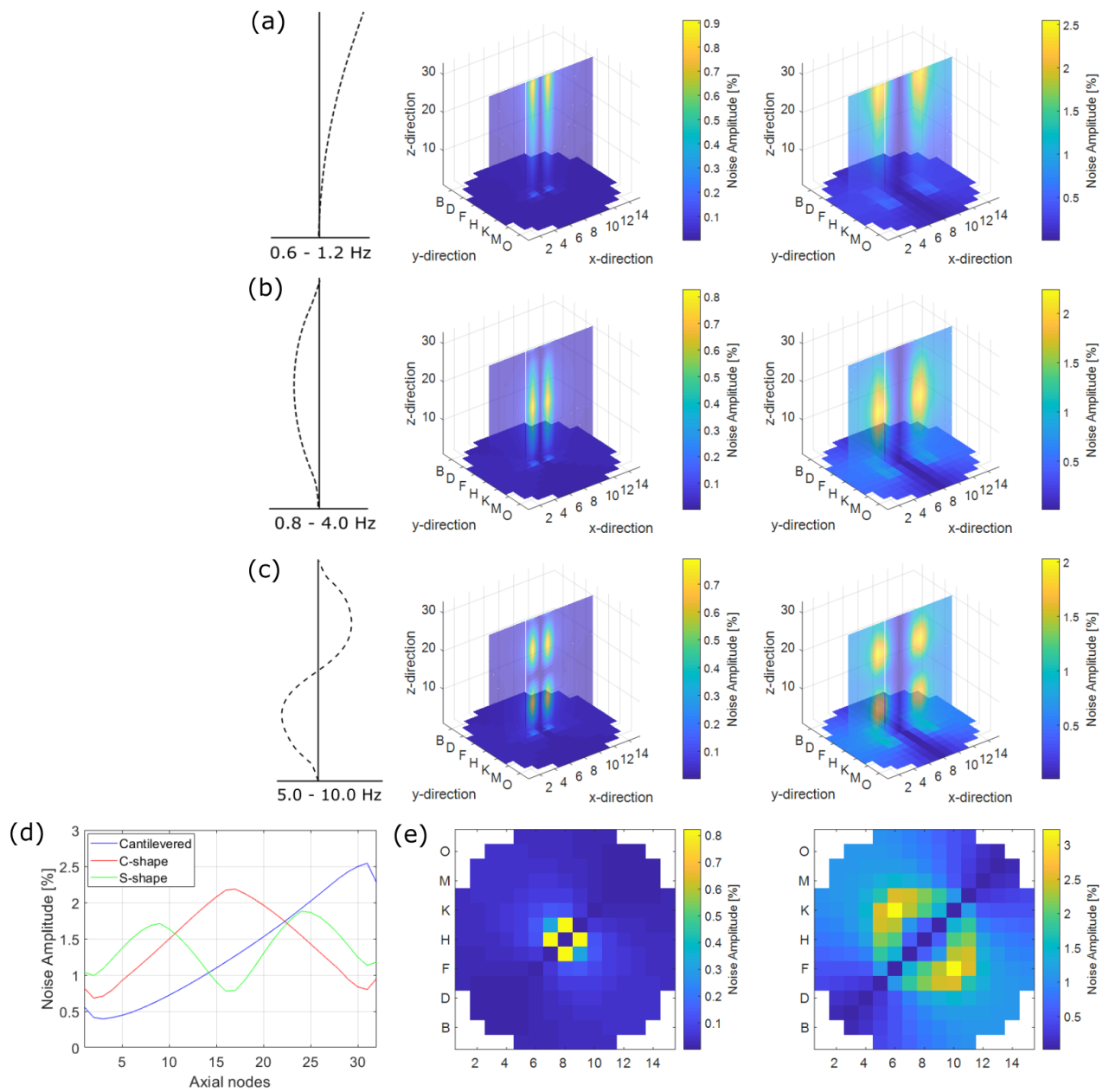
Figure 2: Vibrational modes & their frequency ranges along with the induced noise amplitude due to central FA (*left*) and a *5x5* cluster FA (*right*) vibration in the x-direction in (a) Cantilevered mode, (b) C-shaped mode and (c) S-shaped mode; (d) Axial noise distribution along the 1st neighbouring FA due to *5x5* FA cluster oscillation in the x-direction; (e) Radial noise distribution at the core-middle due to C-shaped mode vibration of central FA (*left*) and a *5x5* cluster (*right*) in the xy-direction.

top region, which is related to the moderator temperature coefficient, that adds to the neutron noise.

Recall that the way neutron noise sources are introduced in the sub-nodes of the FA in S3K, as described in Section 2.2, the fluctuating cross sections in the four sub-nodes of the central node tend to cancel each other. Therefore, it is expected that the lateral movements of the central assembly only impacts the first neighbours along the direction of motion. The results also confirm that the FA, vibrating along the x-direction, introduces the maximum neutron noise in the immediate two neighbouring FAs on either side. If the FA vibrates along the combined x- and y-direction, highest impact of the neutron noise is visible in the four neighbouring FAs along the direction of motion as seen in Figure 2(e)*left*. This behaviour is confirmed for all the three simulated modes of vibrations. Vibration of a *5x5* cluster of FAs also show a symmetric noise behaviour around the introduced noise source, as seen in Figure 2(e)*right*. Note that an expected out-of-phase behaviour is observed in the induced neutron noise due to FA vibrations described in this section. The results are not shown here for the sake of brevity.

4. CONCLUSIONS

From an industrial perspective, it is important to understand the increasing trend of the neutron noise levels in some of the KWU pre-KONVOI reactors operating across Europe, where the main suspect is believed to be the vibration of fuel assemblies with specific designs. An understanding of the natural oscillations of the FAs is therefore required. Until now, the PSI methodology for analysis of neutron noise due to FAs vibrations has focussed on determining the impact of rather simplistic movements of clamped-free FAs. The present work is an extension of this methodology to include realistic movements of FAs such as the cantilevered mode, and the C-shape and S-shape modes. Results of the new developments show that the radial and axial behaviour of the induced neutron noise follow time-dependent complex lateral motion of the FAs, as expected. The improved assembly vibration model is able to introduce time-dependent axial deformations in the fuel assemblies' bowing shapes corresponding to their higher vibrational modes. The obtained results illustrate the maturity of the PSI neutron noise methodology to simulate more complex perturbation scenarios closer to reality.

It is possible to extend such calculations to include modelling of the core barrel vibrations, and combine all core internals' vibrations with thermal-hydraulic fluctuations. As several of these sources might coexist in the reactor core, the final objective is to identify and introduce all possible neutron noise sources in a PWR core, and perform a complete neutron noise analysis with the detector signals to gain further understanding of the observed behaviour of neutron noise in the KWU pre-KONVOI European reactors. It is also suggested to perform validation studies with the frequency-domain based code CORE SIM, which is dedicatedly used for neutron noise analysis applications. Furthermore, the fuel assembly vibration model in S3K is identified to still have several limitations, such as the vibration of all FAs with the same amplitude and frequency, and the inability to impose different vibrational modes to simultaneously vibrating FAs. All such extensions are planned in the future.

ACKNOWLEDGEMENTS

REFERENCES

[1] J. Thie, *Power Reactor Noise*, American Nuclear Society, Illinois, US (1981).

[2] C. Demaziére, P. Vinai, M. Hursin, S. Kollias, J. Herb, "Overview of the CORTEX project," *Proceedings of the International Conference on the Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018)*, Cancun, Mexico, April 22-26, 2018 (2018).

[3] Almaraz Trillo Report, "Neutron noise status in Trillo NPP," technical report CO-12/043, Spain (2012).

[4] M. Seidl, K. Kosowski, U. Schüler, L. Belblidia, "Review of the historic neutron noise behaviour in German KWU built PWRs," *Progress in Nuclear Energy*, **85**, pp. 668-675 (2015).

[5] M. Viebach, C. Lange, N. Brent, M. Seidl, D. Hennig, A. Hurtado, "Simulation of low-frequency PWR neutron flux fluctuations," *Progress in Nuclear Energy*, **117**, Article 103039 (2019).

[6] D. Chionis, A. Dokhane, H. Ferroukhi, G. Girardin, A. Pautz, "PWR Neutron noise phenomenology: Part I-Simulation of stochastic phenomena with SIMULATE-3K," *Proceedings of the International Conference on the Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018)*, Cancun, Mexico, April 22-26, pp. 1001-1012 (2018).

[7] D. Chionis, A. Dokhane, H. Ferroukhi, G. Girardin, A. Pautz, "PWR Neutron noise phenomenology: Part II-Qualitative comparison against plant data," *Proceedings of the International Conference on the Physics of Reactors – Reactor Physics paving the way towards more efficient systems (PHYSOR2018)*, Cancun, Mexico, April 22-26, pp. 1013-1024 (2018).

[8] A. Vidal-Ferrándiz, A. Carreño, D. Ginestar, C. Demaziére, G. Verdú, "Neutronic simulation of fuel assembly vibrations in a nuclear reactor," *Proceedings of the International Conference Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2019)*, Portland, Oregon, August 25-29, 2019 (2019).

[9] V. Verma, C. Demazière, P. Vinai, G. Ricciardi, R. Jacqmin, "Assessment of the neutron noise induced by stationary fuel assembly vibrations in a light water reactor," *Proceedings of the International Conference Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2019)*, Portland, Oregon, August 25-29, 2019 (2019).

[10] H. Ferroukhi, K. Hofer, J. M. Hollard, A. Vasiliev, M. A. Zimmermann, "Core Modelling and Analysis of the Swiss Nuclear Power Plants for Qualified R & D Applications," *Proceedings of the International Conference on the Physics of Reactors – Nuclear Power: A Sustainable Resource (PHYSOR2008)*, Interlaken, Switzerland, Sep 14-19, 41, (2008).

[11] 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," *Proceedings of the International Conference Mathematics & Computational Methods Applied to Nuclear Science & Engineering (M&C 2017)*, Jeju, Korea, April 16-20, 2017 (2017).

[12] D. Chionis, A. Dokhane, L. Belblidia, H. Ferroukhi, G. Girardin, A. Pautz, "Verification and Qualification of the Fuel Assembly Vibration Model in CASMO-5 and SIMULATE-3K," *Soon to be submitted*, (2020).

[13] Kozlowski T., Downar T.J., "OECD/NEA and US NRC PWR MOX/UO2 core transient benchmark – Final Specifications – Revision 2," NEA/NSC/DOC (2006) 20, D (2007).