Efficient Simulation of Fuel Assembly Vibrations in a Nuclear Reactor in Time-Domain

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Introduction

- The mechanical vibration of fuel assemblies has been shown a cause of **neutron noise** and thus, the triggering of power reduction measures.
- This work simulates and analyses the effect in the neutron field of the oscillation of **one single fuel assembly** (FA).
- The problem combines different spatial scales and needs the use of very fine meshes and accurate numerical approximations leading to high computational times. For this reason, in the time domain analysis, efficient solvers are requested.

Time-Dependent Equation

The discretized **neutron diffusion equation** with a **finite element method** (FEM) can be expressed as

$$V^{-1}\frac{d\Phi}{dt} + L\Phi = (1-\beta)M\Phi + \sum_{p=1}^{N_p}\lambda_p X C_p\,,$$

$$\frac{dC_p}{dt} = \beta_p M_1\Phi - \lambda_p C_p, \quad p = 1,\dots,N_p.$$

This system of ODE's is, in general, stiff. Thus, implicit methods are necessary.

Time-Domain

The time-dependent equations can be integrated with the **Euler's backward method** [1] as

$$T^{n+1}\Phi^{n+1} = R^n\Phi^n + \sum_{p=1}^{N_p}\lambda_p e^{-\lambda_p\Delta t_n} X C_p^n\,,$$

where,

$$T^{n+1} = \frac{1}{\Delta t_n}[v^{-1}] + L^{n+1} - \hat{a}M^{n+1}, \quad R^n = \frac{1}{\Delta t_n}V^{-1},$$

$$\hat{a} = 1-\beta+\sum_{p=1}^{N_p}\beta_p\left(1-e^{-\lambda_p\Delta t_n}\right)$$

The neutron precursors can be integrated as

$$C_p^{n+1} = e^{-\lambda_p\Delta t_n}C_p^n + e^{-\lambda_p t_{n+1}}\int_{t_n}^{t_{n+1}} e^{\lambda_p\tau}\beta_p M_1\Phi\, d\tau\,.$$

- This system (large and sparse) is solved at each time step ($\Delta t = 10^{-4}$) with tol $\approx 10^{-14}$.
- The amplitude and the phase of the neutron noise in the frequency domain are obtained by applying the fast Fourier transform (FFT).

Matrix-free strategy

- This strategy computes the **matrix-vector products on the fly** in a cell-based interface.
- The vector that leads to one matrix-vector product takes a vector as input and computes the integrals by multiplying by trial functions.
- The solutions of the linear systems are computed by using the **GMRES** solver with the **block Gauss-Seidel** preconditioner.

Numerical results

Time-domain analysis.

The BIBLIS 2D benchmark is selected to test this methodology for a vibrating FA at 1Hz, 1mm of amplitude in the x direction.

- A refined mesh in the surroundings of the moving FA and cubic polynomials in the FEM are used.
- The results show two effects:
  - A **sinusoidal change in the total power** with a really small amplitude, about $4\cdot 10^{-7}$.
  - A **linear increment** along time of the average value that the thermal-hydraulic feedback will mitigate.
- The fast flux has a big influence in the reactor far away of the moving assembly.

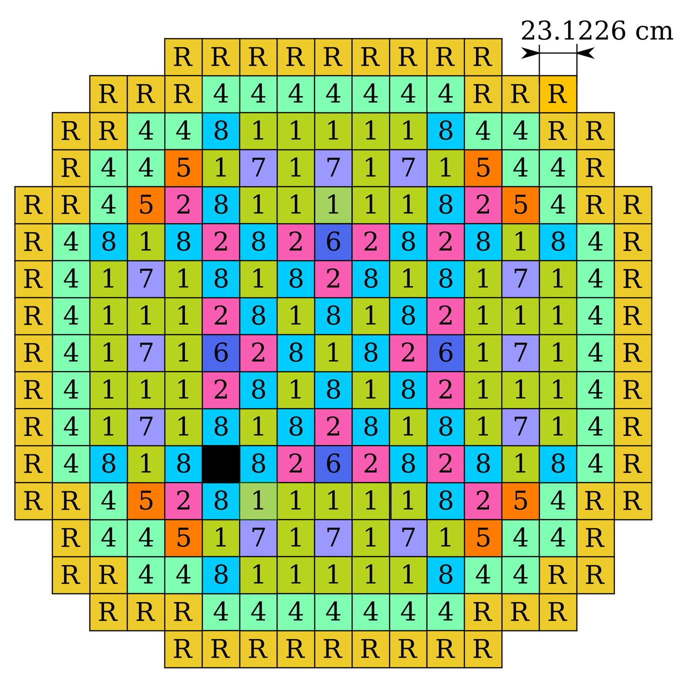

Fig. 1: BIBLIS reactor with the vibration of one fuel assembly.

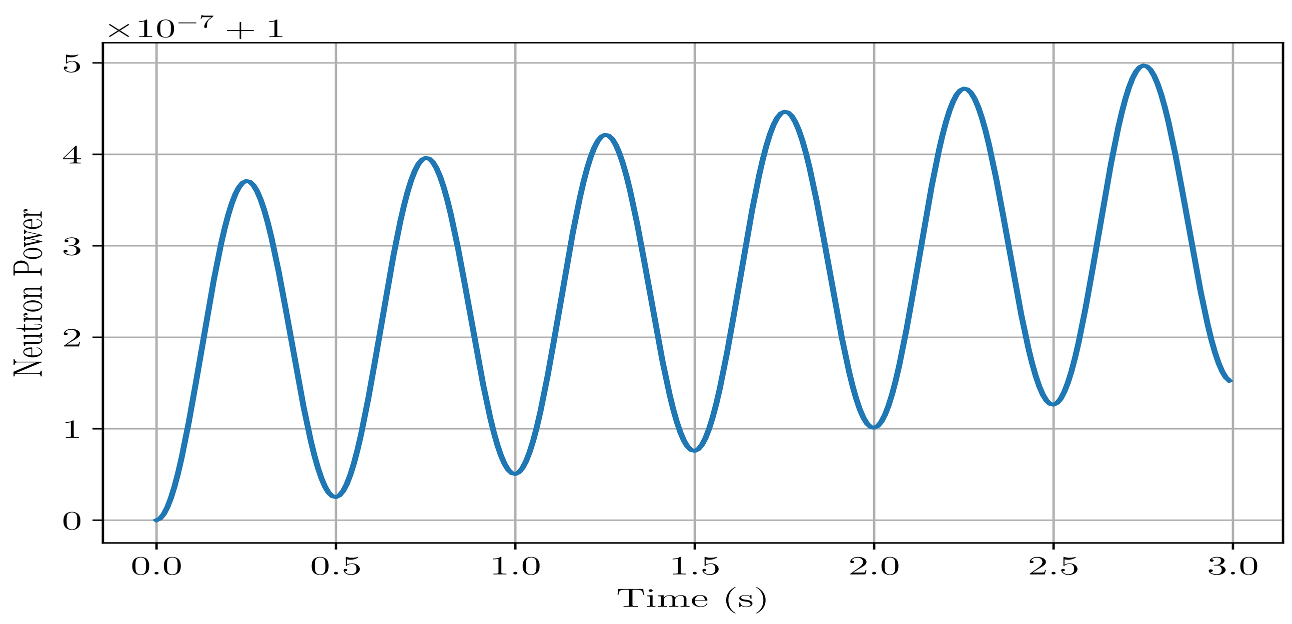

Fig. 2: Relative power evolution.

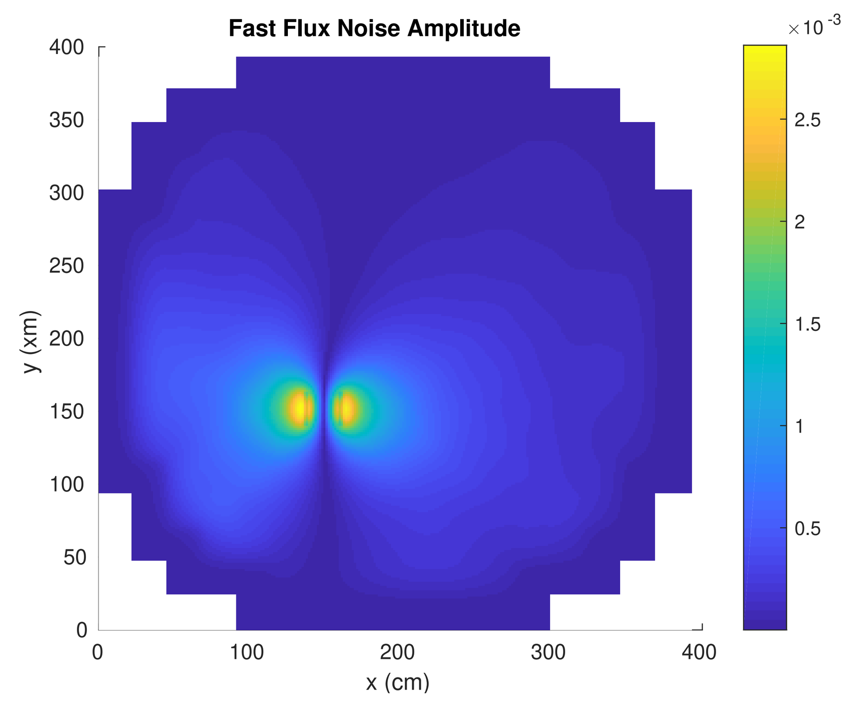

Fig. 3: Fast flux noise amplitude.

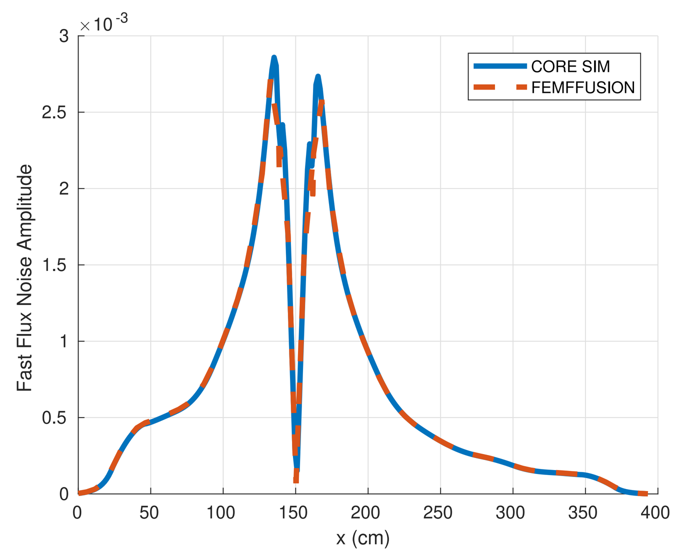

Fig. 4: Fast flux noise phase.

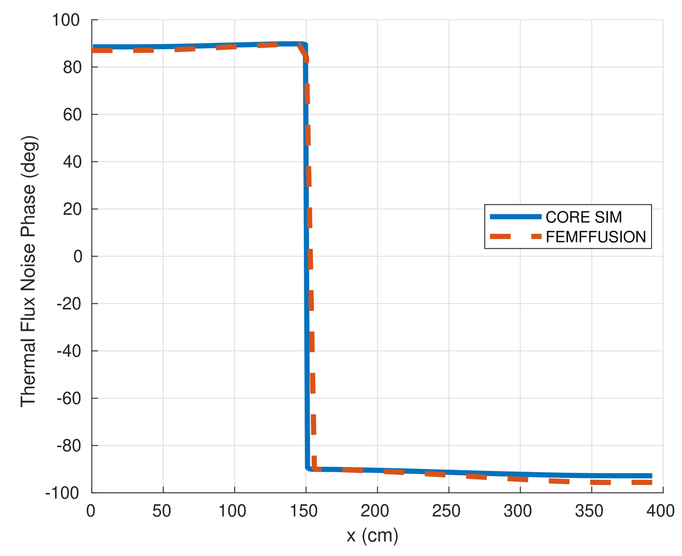

Fig. 5: Fast flux noise amplitude.

Frequency-domain analysis vs Time-domain analysis.

The neutron flux noise obtained with the time-domain analysis is compared with the frequency-domain analysis obtained with the CORE SIM code [2].

- A really **close convergence** is observed for the space dependent neutron noise.

Computational efficiency.

It is compared the use of the full allocated of the matrices (Sparse) and the matrix-free strategy (MatFree).

- **The Matrix-free methodology reduces the CPU memory** by one half.
- **The Matrix-free strategy speeds-up the computation** because it does not assembly the matrices at each time step and the matrix-vector multiplication is faster.

	Memory	CPU time
Sparse	410Mb	146min
MatFree	186Mb	26min

Table 1: Computational results.

References

[1] Vidal-Ferràndiz, A., Fayez, R., Ginestar, D., & Verdú, G. (2016). Moving meshes to solve the time-dependent neutron diffusion equation in hexagonal geometry. Journal of Computational and Applied Mathematics, 291, 197-208.

[2] Demaziere, C., Pazsit, I., Numerical tools applied to power reactor noise analysis. Prog.Nucl.Energy, 51, 67-81, 2009.

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