The COLIBRI programme in CROCUS: characterisation of the fuel rods oscillator

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**CROCUS experiments**
- VOID: void fraction
- COLIBRI: fuel oscillation
- Intrinsic noise experiments
- PETALE: ss. nuclear data
- Hi-fi n. experiments
- γ characterisation

**Instrumentation development**
- Neutron noise stations
- Diamond detector
- Activation and TL dosimetry
- Miniature scintillators
- Data assimilation
- GeN-Foam multiphysics solver
- OFFBEAT: OpenFOAM for fuel beh.

**LOTUS and CARROUSEL**
- Novel detection materials
- Neutron modulation

**Modelling & code development**
- Hi-fi n. experiments
- γ characterisation

Reference:
Lamirand et al. | ANIMMA 2019 | 20.06.2019, Portorož (Slovenia)
**Motivation and goals**

**Initial principle for oscillating fuel rods in CROCUS**

**Investigation of power fluctuations induced by fuel oscillations**

- Fuel vibration as a possible cause of increased noise amplitude in Swiss PWR reactors during normal operation
- Originally, modelling at PSI and experiments at EPFL\(^1\) for the study of coupling between mechanical noise and neutronics

**Modelling of fuel rods oscillation in a pin-by-pin simulator (i.e. DORT-TD)**
Motivation and goals

Investigation of power fluctuations induced by fuel oscillations

- Fuel vibration as a possible cause of increased noise amplitude in Swiss PWR reactors during normal operation
- Originally, modelling at PSI and experiments at EPFL\(^1\) for the study of coupling between mechanical noise and neutronics

Experiments in CROCUS for measuring neutron noise induced by fuel vibration

- Design of an in-core device for lateral oscillation of fuel rods at representative amplitudes and frequencies
- Measurement of the perturbation using neutron noise techniques
- Production of sound experimental data for code validation

Boundary conditions

The CROCUS reactor

• Reactor type
  LWR with partially submerged core
  Room T (controlled) and atmospheric P
  Forced water flow (160 l.min$^{-1}$)
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  Forced water flow (160 l.min\(^{-1}\))

• Operation
  Max. 100 W (zero-power reactor)
  i.e. maximum \(2.5 \times 10^9\) cm\(^{-2}\).s\(^{-1}\)
  Control: B\(_4\)C rods and spillway
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  - Control: B\(_4\)C rods and spillway

- Core dimensions
  - \(\varnothing \)60 cm/100 cm

- Fuel lattices
  - 2-zone (2.5 MR): 336/172-176 rods
  - Inner: UO\(_2\) 1.806 wt\% 1.837 cm
  - Outer: U\(_{\text{met}}\) 0.947 wt\% 2.917 cm
Mechanical design

Boundary conditions for safety

- No friction on fuel cladding or grids
- Movement limited mechanically, not by command
- Only one motor with transmission, for avoiding decoupled oscillation of upper and lower part of the fuel
- Volume and mass above core limited
- Providing calculation results of forces applied to rods
Experimental setup

Mechanical design

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Out-sourced final design\(^1\)
- Up to 18 \(U_{\text{met}}\) rods, easy selection
- Up to 2 Hz and ±2.5 mm radial

Oscillator with core structures, and few pins inserted in the device
Experimental setup

Mechanical design

Boundary conditions for safety
- No friction on fuel cladding or grids
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Out-sourced final design
- Up to 18 $U_{\text{met}}$ rods, easy selection
- Up to 2 Hz and $\pm 2.5$ mm radial
- Top and bottom moving plates
- Rigid transmission via an Al beam
- Up/down position for rod selection
- Cable captor for bottom position
Development and licensing

Adaptation of interfaces
- Authorisation received in June 2015
- New grids installed in January 2017

Tests with dummy rods and weights
- Out-of-vessel in January 2016
- Prototype upgrade
- In-vessel wo/in water in Sept. 2016

Fuel rods modification
- Authorisation received in Jan. 2018
- Modification in the controlled area by the LRS staff in January 2018

Start of the commissioning
- Authorisation received in July 2018

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Motivation and means

For safety purposes

- Definition of operation limits

For experimental purposes

- Knowledge of the perturbation

The device was fully tested

- in air and in water
- out of and in the vessel
- empty, 1 and 18 fuel rods loaded

Installation in the unloading stand (left), and of the loaded device at the top (right)

Installation of the device for testing in the vessel
Motivation and means

For safety purposes
  - Definition of operation limits

For experimental purposes
  - Knowledge of the perturbation

The device was fully tested
  - in air and in water
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  - empty, 1 and 18 fuel rods loaded

With cable data

Cable (blue) and inductive captor (bottom, red) signals provided by the control (1 rod in air, ±1.5 mm and 1 Hz)
Motivation and means

For safety purposes
- Definition of operation limits

For experimental purposes
- Knowledge of the perturbation

The device was fully tested
- in air and in water
- out of and in the vessel
- empty, 1 and 18 fuel rods loaded

With cable data and videos

Motor, inductive captor and pins, and measuring cable

Video of 1 rod in air, ±1.5 mm and 1 Hz
Motivation and means

For safety purposes
- Definition of operation limits

For experimental purposes
- Knowledge of the perturbation

The device was fully tested
- in air and in water
- out of and in the vessel
- empty, 1 and 18 fuel rods loaded

With cable data and videos

Cable and video data (1 rod in air, ±1.5 mm and 1 Hz)

Associated power spectral density in log and linear scale
Results in air

- Reduced amplitude due to play
- Empty: stable, taken as a reference for the top oscillation
- 1 rod: stable, equivalent to empty within the uncertainties
- 18 rods: amplitude increasing with frequency above 1 Hz

Comparison of the oscillator’s behaviour when empty and loaded with 1 rod, in air
Results in air

- Reduced amplitude due to play
- Empty: stable, taken as a reference for the top oscillation
- 1 rod: stable, equivalent to empty within the uncertainties
- 18 rods: amplitude increasing with frequency above 1 Hz

Comparison of the oscillator's behaviour when empty and loaded with 1 rod, in air

Comparison of the oscillator's behaviour when empty and loaded with 18 rods, in air
Results in air

- Reduced amplitude due to play
- Empty: stable, taken as a reference for the top oscillation
- 1 rod: stable, equivalent to empty within the uncertainties
- 18 rods: amplitude increasing with frequency above 1 Hz

Comparison of the oscillator’s behaviour when empty and loaded with 1 rod, in air

Comparison of the oscillator’s behaviour when empty and loaded with 18 rods, in air

Case of a detected hit in the soft bumpers (18 rods, ±2 mm, 1.5 Hz)
Results in water

- Reduced amplitude due to play
- Empty: stable, taken as a reference for the top oscillation
- 1 rod: stable, equivalent to empty within the uncertainties  **Confirmed**
- 18 rods: amplitude increasing with frequency above 1 Hz

Comparison of the oscillator’s behaviour when empty and loaded with 1 rod, in water
Results in water

- Reduced amplitude due to play
- Empty: stable, taken as a reference for the top oscillation
- 1 rod: stable, equivalent to empty within the uncertainties  **Confirmed**
- 18 rods: amplitude increasing with frequency above 1 Hz  **Confirmed**
Based on the shown results, the operation limits were defined and submitted to the Swiss regulator ENSI/IFSN.

**Tests in air**
- ✓ Validated
- ? Not tested
- ✗ Invalidated

**Tests in water**
- ✓ Validated
- ? Not tested
- ✗ Invalidated

### Frequency (Hz)

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<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
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<th>1.1</th>
<th>1.2</th>
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**Comparison of 1 and 18 rods loads**

The chart shows the requested amplitude (mm) against the frequency (Hz), with different layers indicating the amplitude limits. The operation limits are marked with ✓ for validated, ? for not tested, and ✗ for invalidated. The table below summarizes the results for different amplitudes and frequencies, with ✓ for validated, ? for not tested, and ✗ for invalidated.
Conclusion & outlook

A new experimental programme on noise analysis is currently on-going in CROCUS: COLIBRI.

An in-core device for fuel rods oscillation was developed and characterized, which allows the lateral displacement and oscillation of up to 18 $U_m$ fuel rods of the core outer zone, $\pm 2.5$ mm amplitude, and $2$ Hz in frequency.

The programme started in September 2018 with the first experimental campaign within the framework of the Horizon 2020 CORTEX project (this conference, #04-1478).

Thank you for your attention!

Vincent Lamirand  vincent.lamirand@epfl.ch  PI of LRS experimental activities and COLIBRI
Development of an innovative core monitoring technique that allows detecting anomalies in nuclear reactors (excessive vibrations of core internals, flow blockage, coolant inlet perturbations, etc.) using the inherent fluctuations in neutron flux recorded by in-core and ex-core instrumentation.

CORTEX Working Packages (WP)

**WP1 – Development of modelling capabilities for reactor noise analysis:**
- Task 1.1 – Modelling of fluid-structure interactions
- Task 1.2 – Modelling of the effect of fuel assembly vibrations
- Task 1.3 – Generic modelling of reactor transfer function
- Task 1.4 – Methodology for uncertainty and sensitivity analysis applied to reactor noise simulations

**WP2 – Validation of the modelling tools against experiments in research reactors**
- Task 2.1 – Generation of high quality experimental data for code validation
- Task 2.2 – Validation of the computational tools

**WP3 – Development of advanced signal processing and machine learning methodologies for analysis of plant data**
- Task 3.1 – Generation of basic scenarios and simulated data
- Task 3.2 – Advanced data processing in the time- and frequency-domains
- Task 3.3 – Data analysis using machine learning techniques and deep neural networks

**WP4 – Application and demonstration of the developed modelling tools and signal processing techniques against plant data**
- Task 4.1 – Preparation of available measurements and core data; performance of additional measurements; packaging and distribution of tools to project partners
- Task 4.2 – Demonstration of the computational tools and methodologies developed in WP1 and WP3
- Task 4.3 – Recommendations on in-core and out-of-core instrumentations

**WP5 – Knowledge dissemination and education**
- Task 5.1 – Education in reactor dynamics, neutron noise and diagnostics
- Task 5.2 – Knowledge dissemination
- Task 5.3 – Communication