"Listening" to neutron noise – or how to diagnose nuclear reactor systems using the inherent fluctuations in neutron density

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Task Force on Deterministic REActor Modelling at Chalmers University of Technology
Introduction

• Fluctuations always existing in dynamical systems even at steady state-conditions:

\[ X(r,t) = X_0(r,t) + \delta X(r,t) \]
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Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system.
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Conceptual illustration of the possible time-dependence of a measured signal from a dynamical system

➢ Fluctuations carrying some valuable information about the system dynamics

fluctuations or “noise”
Introduction

• Fluctuations could be used for “diagnostics”, i.e.:
  
  — Early detection of anomalies
  
  — Estimation of dynamical system characteristics
  
  … even if the system is operating at steady-state conditions

➢ Example of nuclear reactors
Characteristics of nuclear reactors

• Nuclear reactors = large and complex systems
Characteristics of nuclear reactors
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Characteristics of nuclear reactors

reactor core
Characteristics of nuclear reactors

reactor core

fuel assembly
Characteristics of nuclear reactors

reactor core  fuel assembly  fuel pin
Characteristics of nuclear reactors

- Reactor core
- Fuel assembly
- Fuel pin
- Fuel pellet
Characteristics of nuclear reactors

- Neutron detectors present both in-core and ex-core:
  - Ex-core neutron detectors
  - Fixed in-core neutron detectors
  - Movable in-core neutron detectors

- Advantage: “sense” perturbations even far away from the perturbations
- Disadvantage: western-type reactors do not always contain many in-core neutron detectors
Noise diagnostics in nuclear reactors

- Neutron noise diagnostics requires establishing relationships between neutron detectors and possible perturbations

- Could be done using the neutron transport equation (Boltzmann equation) or some simpler forms of it:

\[
\frac{1}{v(E)} \frac{\partial}{\partial t} \psi(r, \Omega, E, t) \\
= -\Omega \cdot \nabla \psi(r, \Omega, E, t) - \sum_i \psi(r, E, t) \psi(r, \Omega, E, t) \\
+ \int_0^\infty \int_0^{4\pi} \sum_s \left[ (r, \Omega' \rightarrow \Omega, E' \rightarrow E, t) \psi(r, \Omega', E', t) \right] d\Omega' dE' \\
+ \frac{1}{4\pi} \int_0^t \int_0^\infty \nu(E') \sum_f \left[ (r, E', t') \phi(r, E', t') \right] \left[ (1 - \beta) \chi_p(E) \delta(t - t') + \sum_{i=1}^{N_d} \chi_i^d(E) \lambda_i \beta_i e^{-\lambda_i(t-t')} \right] dt' dE'
\]
Noise diagnostics in nuclear reactors

- Calculations to solve the system of equations for noise applications can be performed:
  - In the time- or frequency-domain
  - In linear or non-linear theory
  - Using diffusion or transport theory
  - Using deterministic or probabilistic (Monte Carlo) approaches
  - Using a coarse mesh or fine mesh representation of the phase space
Noise diagnostics in nuclear reactors

- Example of a travelling perturbation @ 1Hz
Noise diagnostics in nuclear reactors

- Calculations equivalent to estimating the reactor transfer function $G(r, r_p, \omega)$
Noise diagnostics in nuclear reactors

- But noise diagnostics requires the inversion of the reactor transfer function $G(r, r_p, \omega)$
Noise diagnostics in nuclear reactors

- But noise diagnostics requires the inversion of the reactor transfer function \( G(r, r_p, \omega) \)

- Machine learning could be used for that purpose
- Unfolding possible even if very few detectors available, due to the spatial correlations existing between a localized perturbation and its effect throughout the nuclear core
- EU-funded project CORTEX
Noise diagnostics in nuclear reactors

• **CORTEX**: CORe monitoring Techniques and Experimental validation and demonstration – EU funding.

  - Chalmers coordinating the project
  - 20 partners (18 from EU + 1 from Japan + 1 from USA)


  Follow the project on LinkedIn as well!

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754316.
Noise diagnostics in nuclear reactors

- CORTEX aims:
  - Developing high fidelity tools for simulating stationary fluctuations
  - Validating those tools against experiments to be performed at research reactors

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Noise diagnostics in nuclear reactors

- CORTEX aims:
  - Developing high fidelity tools for simulating stationary fluctuations
  - Validating those tools against experiments to be performed at research reactors
  - Developing advanced signal processing and machine learning techniques (to be combined with the simulation tools)
  - Demonstrating the proposed methods for both on-line and off-line core diagnostics and monitoring

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Noise diagnostics in nuclear reactors

- Machine learning able to correctly identify and localize the type of perturbations existing in a nuclear core:
Noise diagnostics in nuclear reactors

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Prediction

Ground truth

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Noise diagnostics in nuclear reactors

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Prediction

Ground truth

© A. Durrant, G. Leontidis, S. Kollias (University of Lincoln/University of Aberdeen, UK)

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Conclusions and outlook

• Core diagnostics leading to improved reactor safety

• CORTEX project potentially having a large impact if successful

• Core diagnostics = mix between
  – Basic reactor physics and neutron transport
  – Computational reactor physics
  – Experimental reactor physics
  – Advanced signal analysis
  – Artificial intelligence

… with applications to large industrial installations
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