CORTEX

Core monitoring techniques and experimental validation and demonstration

Neutron noise-based core monitoring for identifying and characterizing anomalies and their root causes in operating reactors

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

Introduction

- Ageing fleet of reactors and more frequent operational problems to be expected

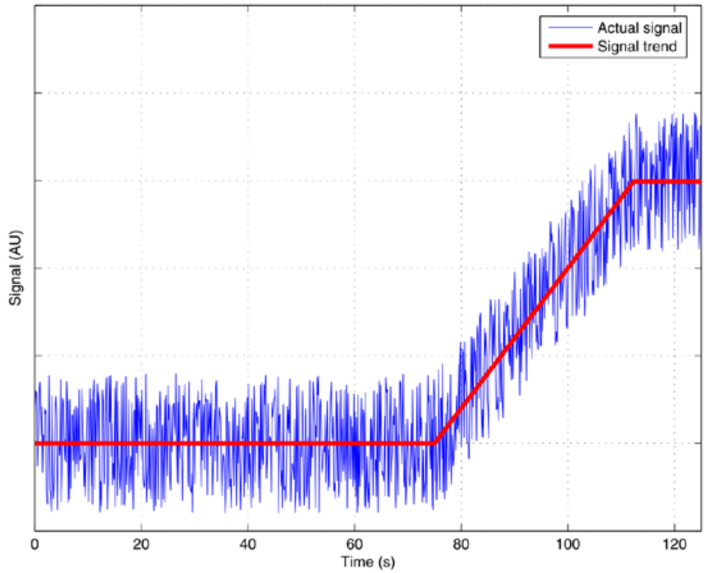
- Recent problems observed in pre-KONVOI PWRs in Germany, Switzerland and Spain

➢ Of value to:

  - Monitor the instantaneous state of the reactor during operation
  - Detect possible anomalies early on
  - Pinpoint the reasons of the anomalies

Introduction

- Fluctuations always existing in reactors even at steady state-conditions (due to turbulence, vapour generation, mechanical vibrations, etc.)



Conceptual illustration of the possible time-dependence of a process signal from a nuclear reactor

$$X(\mathbf{r},t) = X_0(\mathbf{r},t) + \delta X(\mathbf{r},t)$$

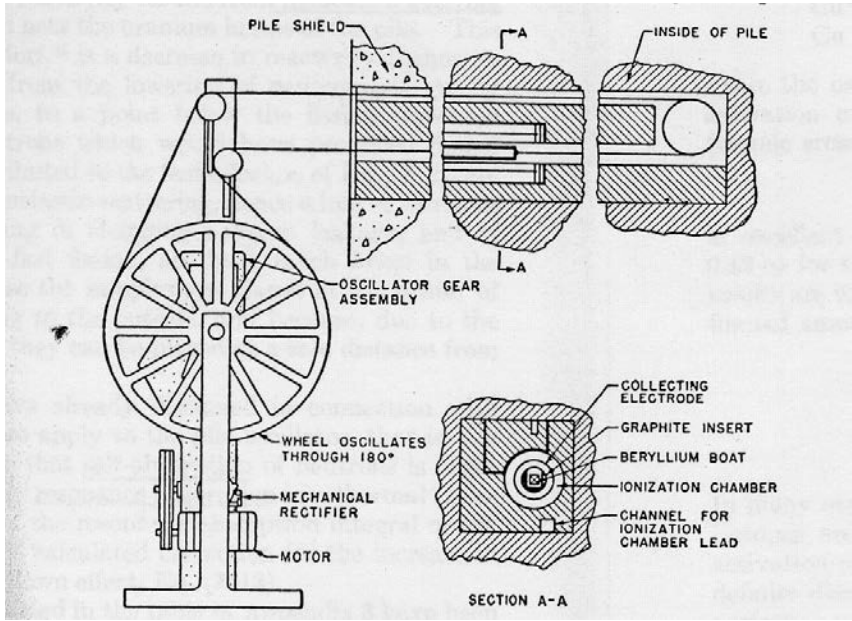
- ➢ Fluctuations carrying some valuable information about the system dynamics
- ➢ Fluctuations could be used for core diagnostics: "noise analysis"

Introduction

- Presentation aimed at:
  - Giving a brief account of the capabilities of core monitoring using noise analysis
  - Presenting the European project CORTEX (started on September 1st, 2017)

Early development in noise analysis

- Oscillator experiments in the Clinton Pile at ORNL, USA



➢ Response in neutron flux corresponding to a local (but stationary) excitation of the system deviating from point-kinetics: local component of the neutron noise (1949)

Early development in noise analysis

- Detection of excessive vibrations of control rods in the Oak Ridge Research Reactor and the High Flux Isotope Reactor (1971)

➢ Noise analysis was born

- First applications in commercial reactors:
  - Core-barrel vibrations at the Palisades plant, USA (1975)
  - Estimation of in-core coolant velocity in German BWRs (1979)

Some examples of core monitoring using noise analysis

- Control rod vibrations:
  - Modelling of the perturbations as:

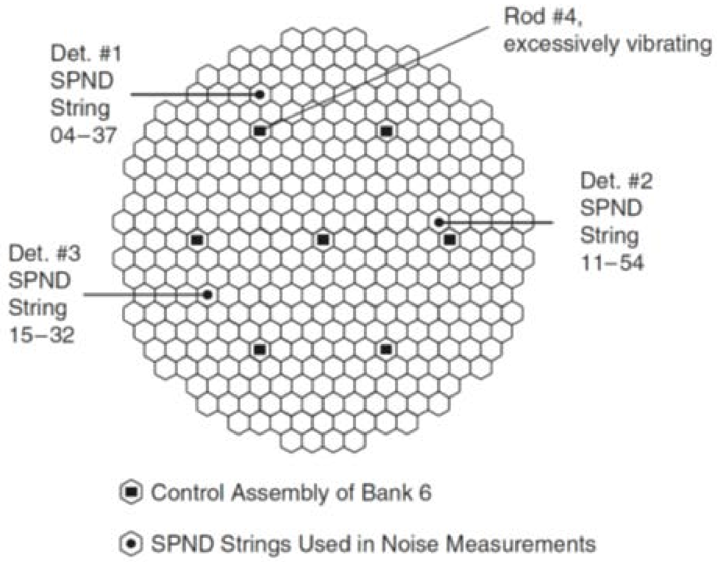
$$\delta\Sigma(\mathbf{r},t) = \gamma\left[\delta\left(\mathbf{r} - \mathbf{r}_p - \underline{\varepsilon}(t)\right) - \delta\left(\mathbf{r} - \mathbf{r}_p\right)\right]$$

➢Resulting induced neutron noise (weak absorber formulation):

$$\delta\phi(\mathbf{r},\omega) = \gamma\underline{\varepsilon}(\omega)\cdot\nabla_{\mathbf{r}_p}\left[G(\mathbf{r},\mathbf{r}_p,\omega)\phi_0(\mathbf{r})\right]$$

Some examples of core monitoring using noise analysis

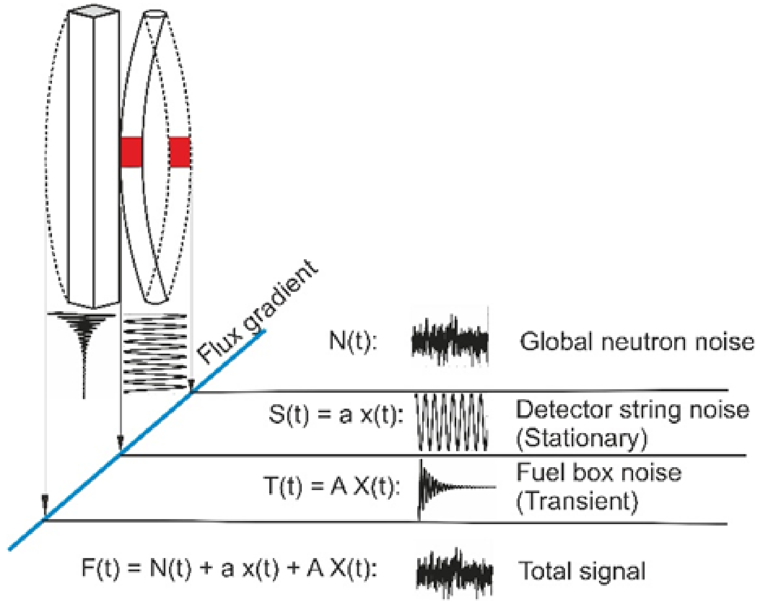
- Control rod vibrations:
  - ➢Root finding (minimization) procedure to find the position of the moving rod
  - ➢Possibility to use Artificial Neural Networks for the unfolding



Layout of the detectors used for the localization of an excessively vibrating control rod out of 7 possible ones in the Hungarian Paks-2 PWR in 1985.

Some examples of core monitoring using noise analysis

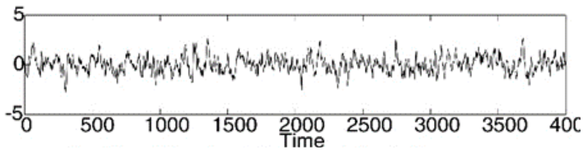
- Anomaly characterization and localization, e.g. detection of detector tube impacting:



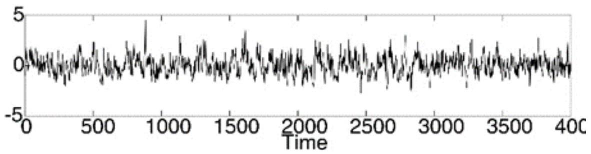
Conceptual illustration of the different components of the neutron noise signal in case of vibrations and impacting.

Some examples of core monitoring using noise analysis

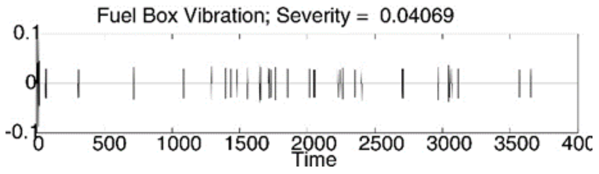
- Anomaly characterization and localization, e.g. detection of detector tube impacting:
  - Qualitative analysis using spectral methods – need of reference measurements
  - Quantitative analysis using wavelet methods – can deal with intermittences

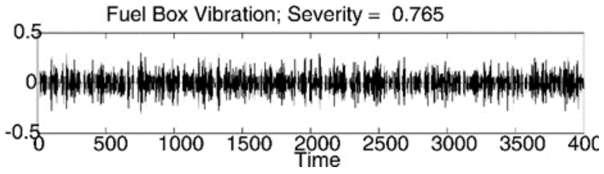


a) Detector signal LPRM 18.3



b) Detector signal LPRM 03.3

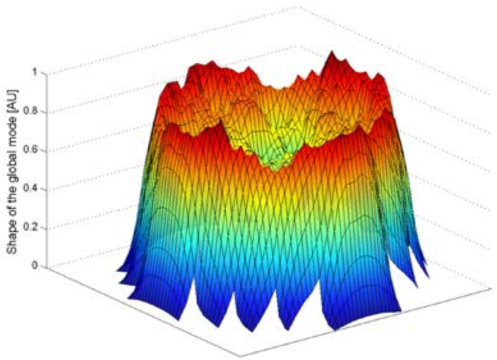


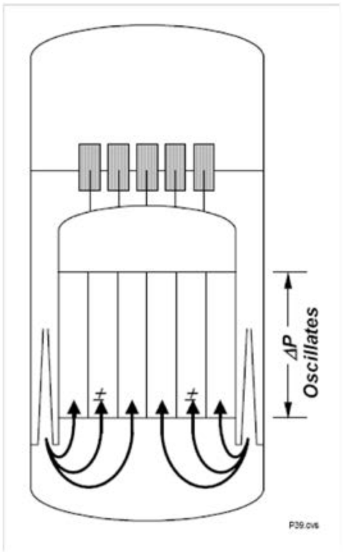


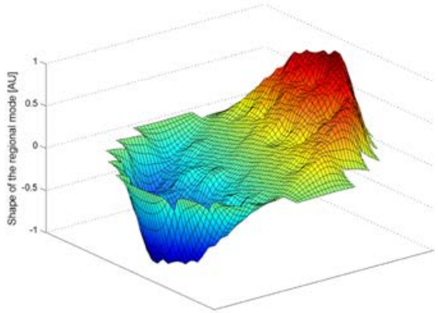
Wavelet-based analysis of two LPRM signals at the Swedish Barsebäck-1 BWR in 1994: LPRM 18.3 (left) and LPRM 03.3 (right). The original signals are represented on the top figures, whereas the components of the signals related to fuel impacting are given on the bottom figures.

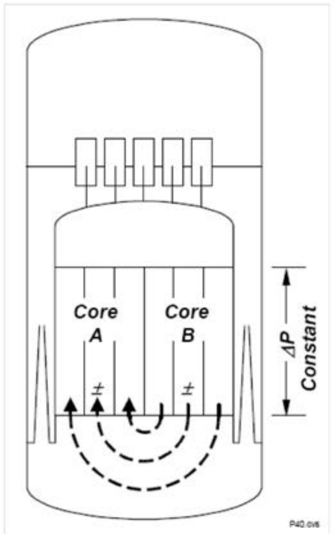
Some examples of core monitoring using noise analysis

- BWR instabilities:
  - Different types of instabilities (global, regional, and local)









Conceptual illustration of global oscillations (left) and of regional oscillations (right).

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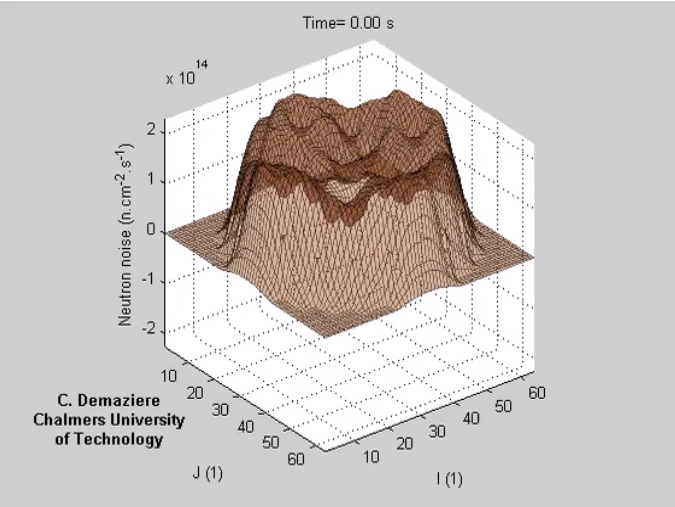

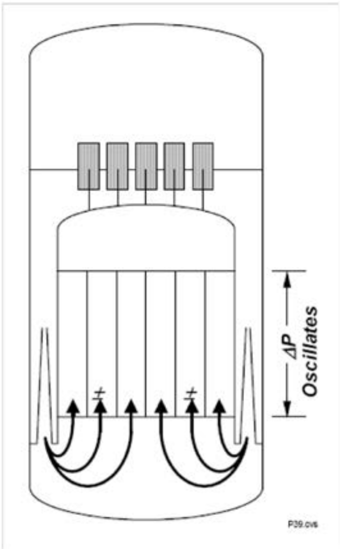

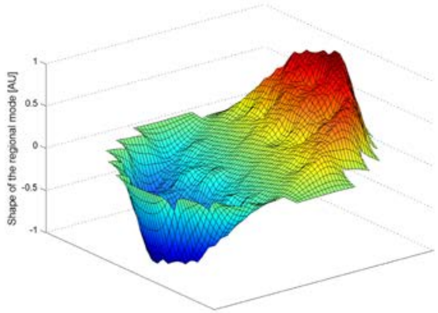

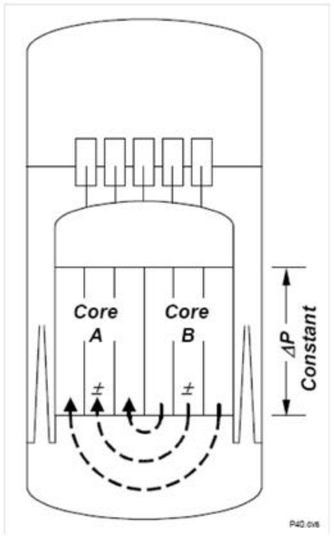

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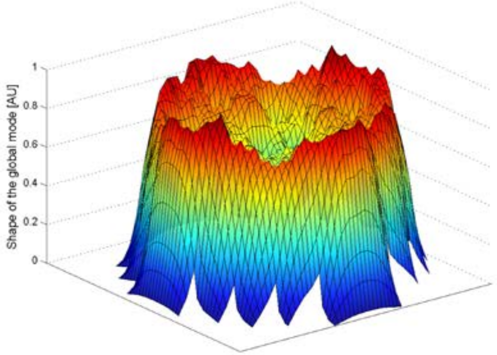

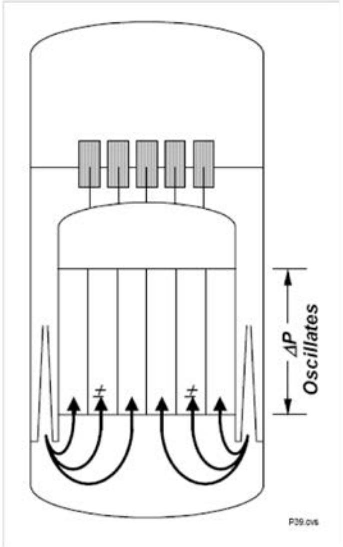

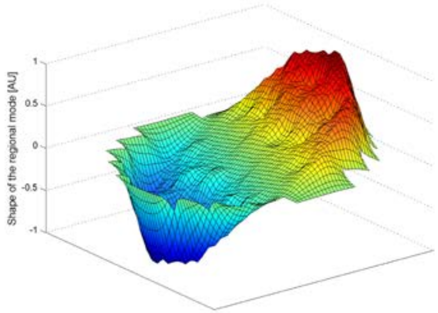

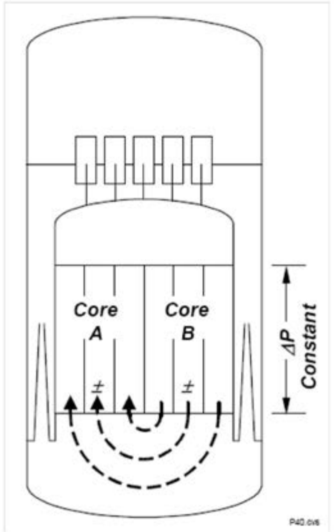

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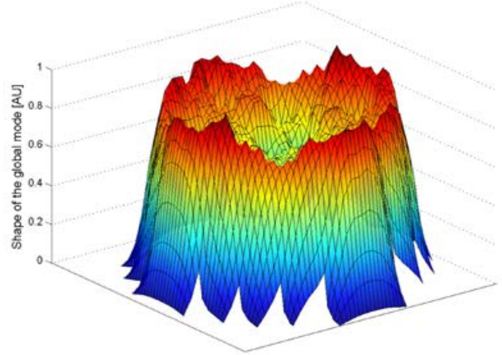
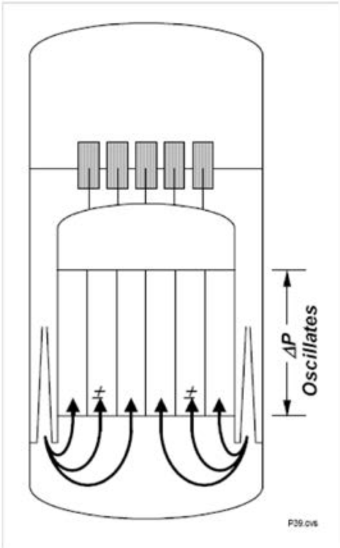
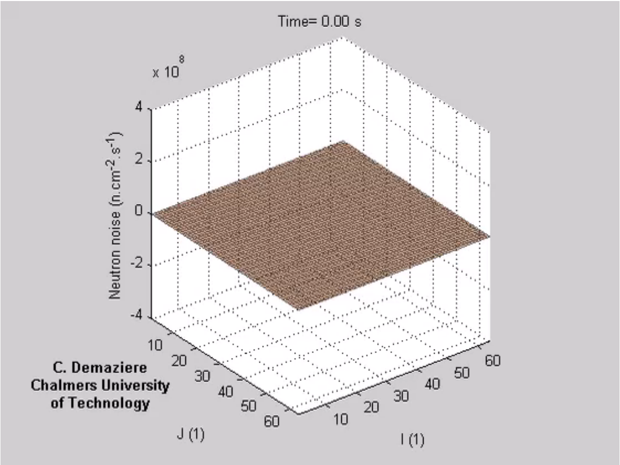
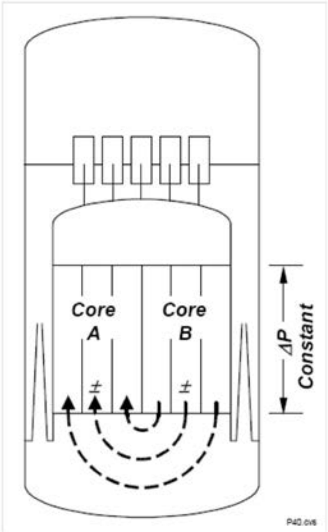








Conceptual illustration of global oscillations (left) and of regional oscillations (right).

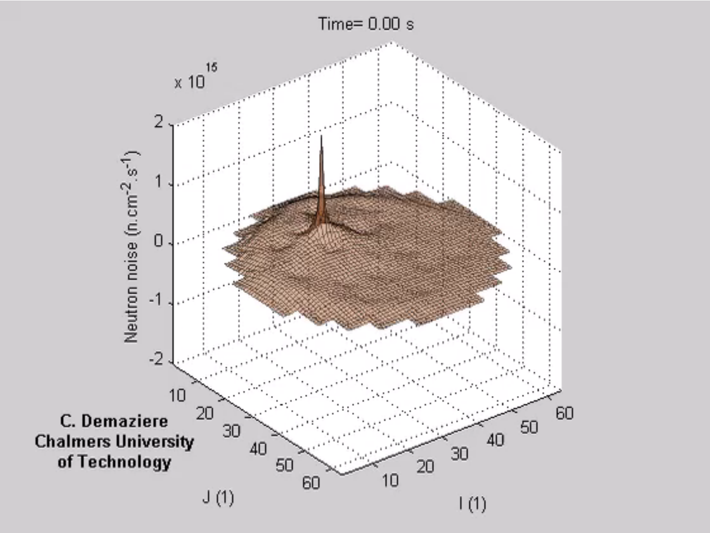
Some examples of core monitoring using noise analysis

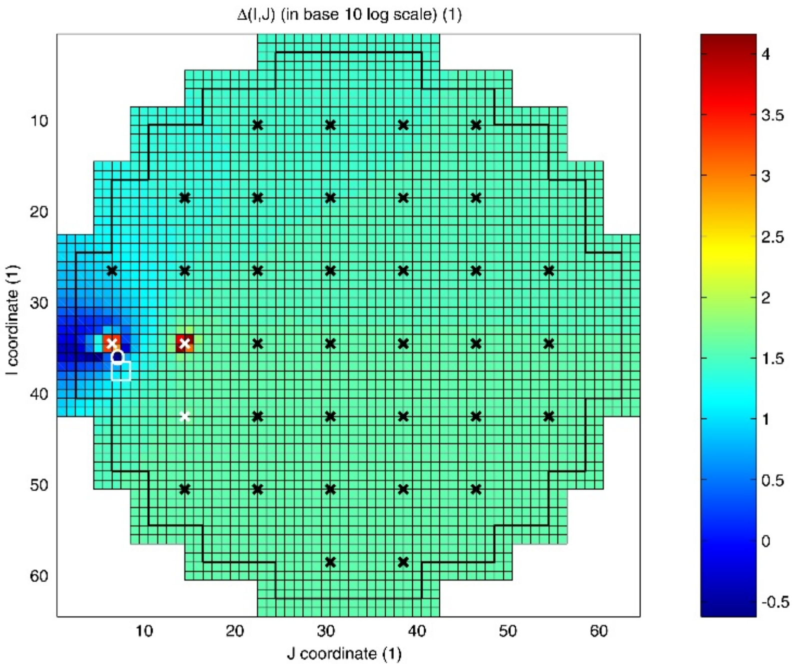
- BWR instabilities:
  - Separation of global and regional oscillations using a partial factorization technique:

$$\delta\phi(\mathbf{r},t)=\frac{\int_V \delta\phi(\mathbf{r},t)\phi_0(\mathbf{r})\,dV}{\int_V \phi_0^2(\mathbf{r})\,dV}\phi_0(\mathbf{r})+\delta\psi(\mathbf{r},t)$$

Some examples of core monitoring using noise analysis

- BWR instabilities:
  - Localization of possible local oscillations by a minimization procedure:



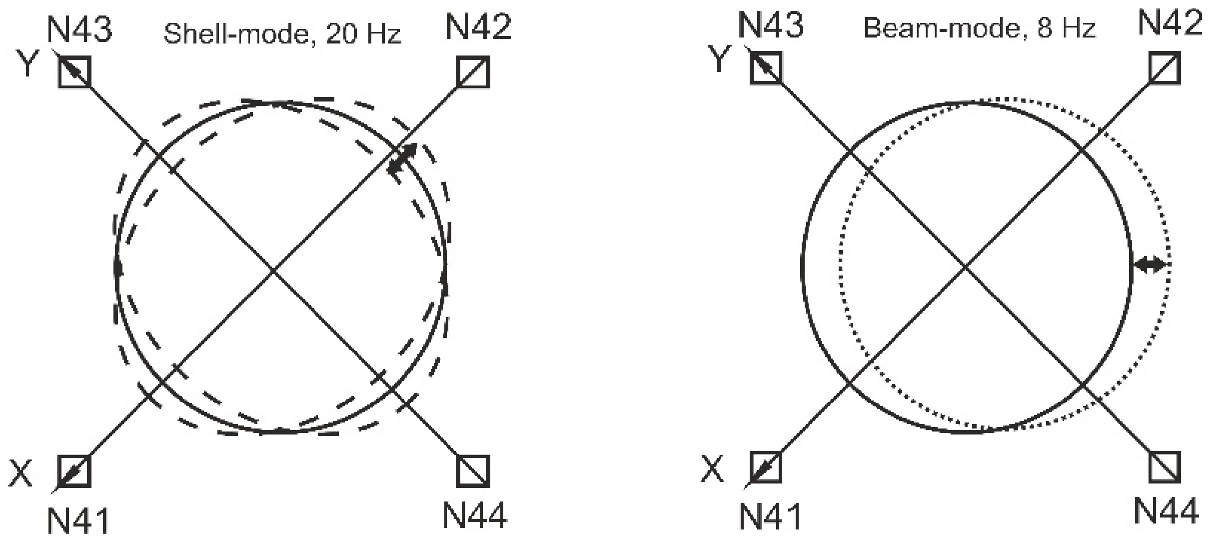


$$\Delta\left(\mathbf{r}\right)=\sum_{A,B}\left[\frac{\delta\phi\left(\mathbf{r}_A,\omega\right)}{\delta\phi\left(\mathbf{r}_B,\omega\right)}-\frac{G\left(\mathbf{r}_A,\mathbf{r},\omega\right)}{G\left(\mathbf{r}_B,\mathbf{r},\omega\right)}\right]^2$$

Result of the localization algorithm in the Forsmark-1 case (local instability event). The unseated fuel element is marked with a square, and the noise source identified by the localization algorithm with a circle; the detectors that were used in the localization search are marked by white crosses, whereas the detectors that were not used are marked by black crosses.

Some examples of core monitoring using noise analysis

- Core barrel vibrations:
  - Several possible modes of vibrations (beam mode and shell mode):



Conceptual representation of the beam- and shell-mode vibrations of the core barrel in PWRs
(the ex-core detectors are shown as squares and labelled N4X).

Some examples of core monitoring using noise analysis

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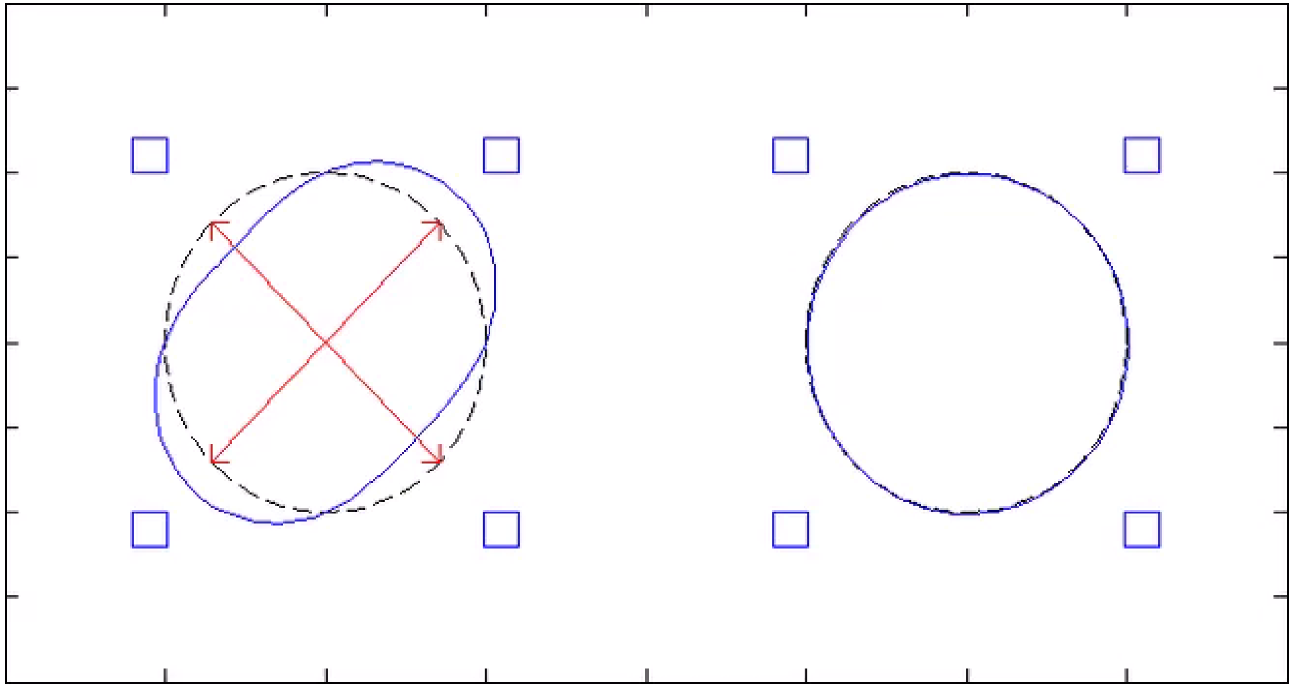


Conceptual representation of the beam- and shell-mode vibrations of the core barrel in PWRs (the ex-core detectors are shown as squares).

Some examples of core monitoring using noise analysis

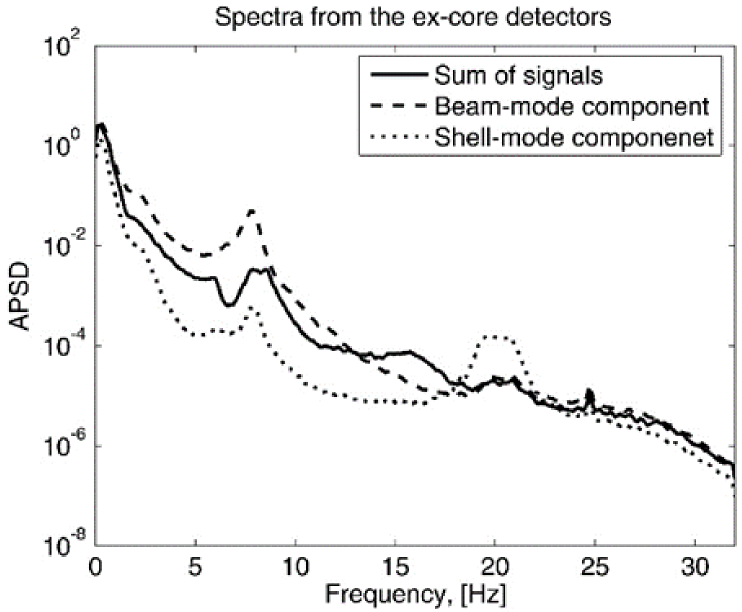
- Core barrel vibrations:
  - Mode separation:

Beam mode:

$$\begin{cases} x(t) \propto \delta\phi_1(t) - \delta\phi_2(t) \\ y(t) \propto \delta\phi_3(t) - \delta\phi_4(t) \end{cases}$$

Shell mode:

$$d(t) \propto \delta\phi_1(t) + \delta\phi_2(t) - \delta\phi_3(t) - \delta\phi_4(t)$$



Ex-core neutron detector spectra illustrating the different core barrel vibration modes.
The measurement data were obtained at the Swedish Ringhals-3 PWR.

Overview of CORTEX

- Need for core monitoring techniques recently demonstrated by the increase in the neutron noise levels in some Spanish, German, and Swiss Pre-Konvoi PWRs

➢ Need to develop the necessary tools before the problems occur

➢ CORTEX project proposal submitted to the Euratom 2016-2017 work program (CORe monitoring Techniques and EXperimental validation and demonstration)

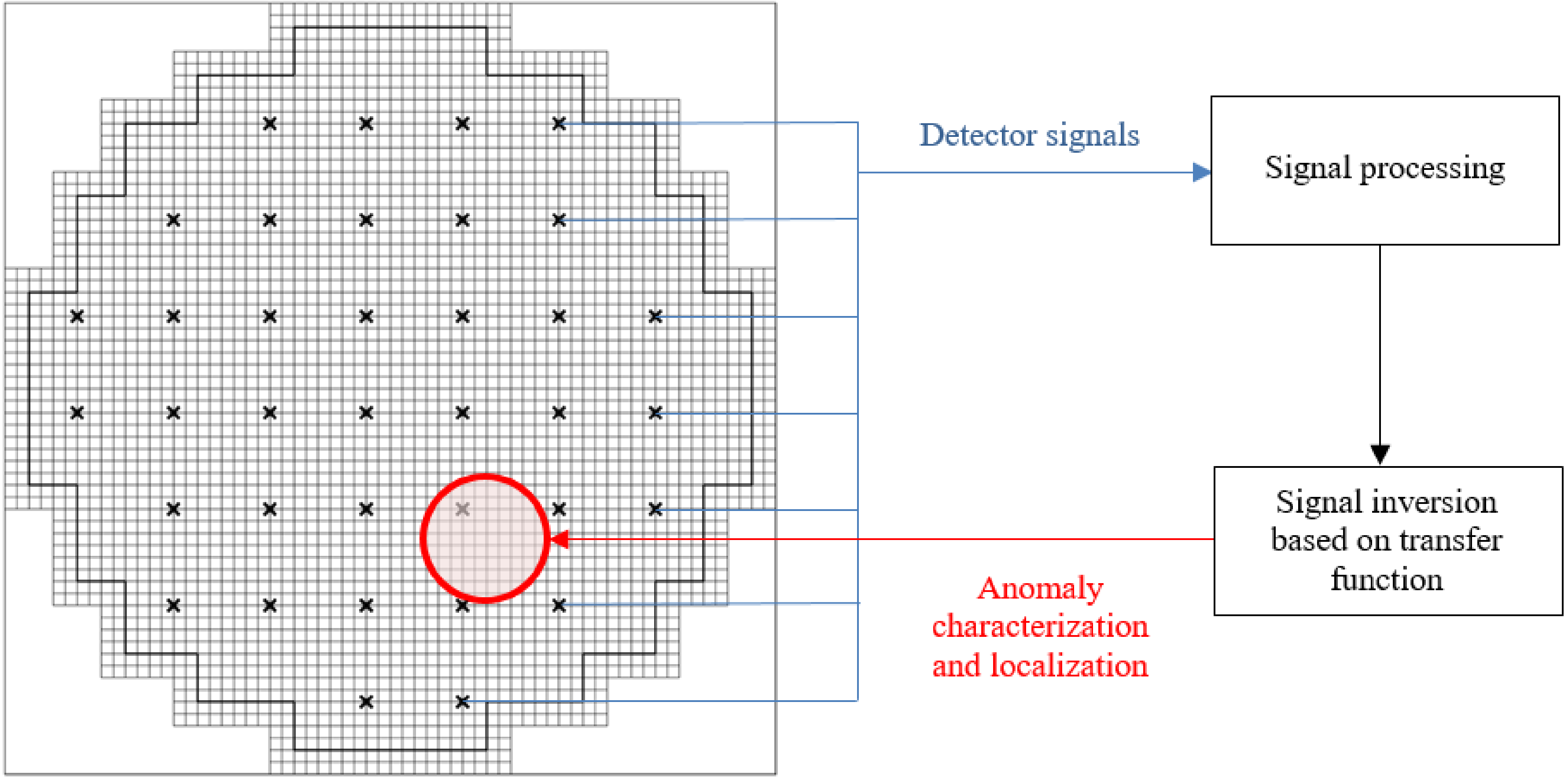
➢ CORTEX obtained the NUGENIA label in August 2016

➢ CORTEX project approved for funding by the European Commission in February 2017

➢ CORTEX project started on September 1st, 2017

Overview of CORTEX

- Project concept:



Overview of CORTEX

- Signal analysis techniques of help…

  but insufficient for backtracking the nature and spatial distribution of possible anomalies

➢Need to be able to invert the reactor transfer function $G\left(\mathbf{r},\mathbf{r}_{\mathbf{p}},\omega\right)$

$$\delta\phi\left(\mathbf{r},\omega\right) \leftarrow \boxed{G\left(\mathbf{r},\mathbf{r}_{\mathbf{p}},\omega\right)} \leftarrow \delta P\left(\mathbf{r}_{\mathbf{p}},\omega\right)$$

Overview of CORTEX

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Overview of CORTEX

- Project 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
  - Disseminating the knowledge gathered from within the project to stakeholders in the nuclear sector

Overview of CORTEX

- Project participants:
  - Project led and coordinated by Chalmers University of Technology
  - 18 European organizations involved in the project:
    - CEA and LGI Consulting (France)
    - Centre for Energy Research, Hungarian Academy of Sciences – MTA EK (Hungary)
    - EPFL, KKG, PSI (Switzerland)
    - GRS, ISTec, TIS, PEL, TU Dresden and TU Munich (Germany)
    - Institute of Communication & Computer Systems - National Technical University of Athens (Greece)
    - UJV (Czech Republic)
    - University of Lincoln (UK)
    - UPM and UPV (Spain)

Overview of CORTEX

- Project participants:
  - 2 non-European organizations formally involved in the project:
    - KURRI (Japan)
    - AMS Corp (USA)

    + 1 organization informally involved in the project: Nagoya University (Japan)

  - 5 additional organizations involved in the Advisory End-User Group:
    - IRSN (France)
    - KKG (Switzerland)
    - PEL (Germany)
    - Ringhals (Sweden)
    - Tractebel (Belgium)
    - CNAT (Spain)
    - AREVA (Germany)
    - Westinghouse Electric Sweden AB (Sweden)

Overview of CORTEX

- Proposed technical Work Packages (WPs):
  - WP1: Development of modelling capabilities for reactor noise analysis (lead organization: Chalmers University of Technology, Sweden)

Objectives:

- To develop modelling capabilities allowing the determination, for any reactor core, of the fluctuations in neutron flux resulting from known perturbations applied to the system
- To express such perturbations as either fluctuations of macroscopic cross-sections based on expert opinion, or in more physical terms, such as vibrations of components (FSI)
- To evaluate the uncertainties associated to the estimation of the reactor transfer function and to perform sensitivity analysis in reactor dynamic calculations

Overview of CORTEX

- Proposed technical Work Packages (WPs):

  - WP2: Validation of the modelling tools against experiments in research reactors (lead organization: PSI/EPFL, Switzerland)

  Use of the AKR-2 (TU Dresden) and CROCUS (EPFL) research reactors for reactor transfer function validation

  Objectives:
  - ➢ Validation of the modelling tools produced in WP1 against experimental measurements: localized absorber of variable strength + moving absorber
  - ➢ Development of new detectors

Overview of CORTEX

- Proposed technical Work Packages (WPs):

  - WP3: Development of advanced signal processing and machine learning methodologies for analysis of plant data (lead organization: University of Lincoln, UK)

  Objectives:

  - Detection of abnormal fluctuations and their classification
  - Inversion of the reactor transfer function
  - Handling of the scarcity of in-core instrumentation
  - Handling of intermittences

Overview of CORTEX

- Proposed technical Work Packages (WPs):

  - WP4: Application and demonstration of the developed modelling tools and signal processing techniques against plant data (lead organization: GRS, Germany)

  Objectives:

  - ➢Demonstration of the applicability and usefulness of the tools
  - ➢Detection of abnormal fluctuations, understanding of their origin and classification according to their safety impact
  - ➢Recommendations about in-core/out-of-core instrumentation

Overview of CORTEX

- Other Work Packages (WPs):
  - WP5: Knowledge dissemination and education (lead organization: Chalmers University of Technology, Sweden)

Objectives:

- ➢ Designing of short courses on reactor dynamics, reactor neutron noise, and signal processing methods
- ➢ Development of a workshops series: (a) to present the application of the models and methodologies to real cases; and (b) to discuss recommendations and improvements for monitoring reactor operations and future advancements with end-users
- ➢ Setting up communication tools for the public and interested stakeholders

Overview of CORTEX

- Other Work Packages (WPs):

  - WP6: Project management (lead organization: Chalmers University of Technology, Sweden)

  Objectives:

  - Timely and qualitative achievement of the project results to reach the objectives and contractual commitments

Conclusions

- Core monitoring becoming increasingly important
- Need to develop the necessary tools and expertise before the problems occur
- CORTEX gathering a cross-disciplinary team of experts for developing core monitoring techniques for industrial applications
- Interested in the CORTEX project and its outcome? Let us know!
- Follow the project on LinkedIn, Twitter and Facebook and at http://cortex-h2020.eu/

CORTEX

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