

NOISE-BASED CORE MONITORING AND DIAGNOSTICS – OVERVIEW OF THE CORTEX PROJECT

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Abstract

This paper gives an overview of the CORTEX project, which is a Research and Innovation Action funded by the European Union in the Euratom 2016-2017 work program, under the Horizon 2020 framework. CORTEX, which stands for CORE monitoring Techniques and EXperimental validation and demonstration, aims at developing an innovative core monitoring technique that allows detecting anomalies in nuclear reactors, such as excessive vibrations of core internals, flow blockage, coolant inlet perturbations, etc. The technique is based on primarily using the inherent fluctuations in neutron flux recorded by in-core and ex-core instrumentation (often referred to as neutron noise), from which the anomalies will be differentiated depending on their type, location and characteristics. In addition to be non-intrusive and not requiring any external perturbation of the system, the method allows the detection of operational problems at a very early stage. Proper actions could thus be taken by utilities before such problems have any adverse effect on plant safety and reliability.

1. Introduction

Being able to monitor the state of nuclear reactors while they are running at nominal conditions is extremely advantageous. The early detection of anomalies gives the possibility for the utilities to take proper actions before such problems lead to safety concerns or impact plant availability. The

analysis of measured fluctuations of process parameters (primarily the neutron flux) around their mean values has the potential to provide non-intrusive on-line core monitoring capabilities. These fluctuations, often referred to as noise, are formally defined as:

$$\delta X(\mathbf{r}, t) = X(\mathbf{r}, t) - X_0(\mathbf{r}, t) \quad (1)$$

where $X(\mathbf{r}, t)$ is the actual signal and $X_0(\mathbf{r}, t)$ is the signal trend (usually obtained after filtering the original signal). This is conceptually illustrated in Figure 1. The variables \mathbf{r} and t represent space (i.e. position) and time, respectively. As a rule, such fluctuations arise either from the turbulent character of the flow in the core, from coolant boiling (in the case of two-phase systems), or from mechanical vibrations of reactor internals, and to a much smaller extent from the stochastic character of nuclear reactions. Because such fluctuations carry valuable information concerning the dynamics of the reactor core, one can infer some information about the system state under certain conditions.

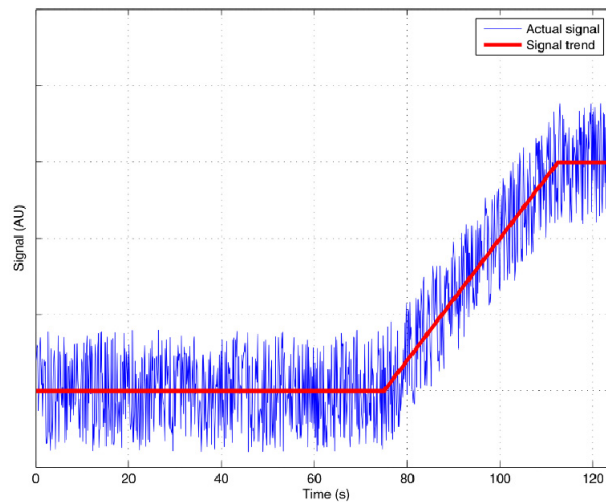


Figure 1 Conceptual illustration of the fluctuations observed in process parameter measurements. The fluctuations are defined as the deviation of the actual signal from its trend.

Recovering from the detector readings the anomaly responsible for the observed neutron flux fluctuations (a process often referred to as noise source unfolding) was successfully demonstrated in the past on a research scale both with parametric and non-parametric inversion methods and both on simulated data and measured signal. However, in all such cases, the inversion algorithms were based on the assumption of a simple homogeneous reactor model, which limited the applicability of the unfolding procedure. Being able to determine the so-called reactor transfer function for non-homogeneous reactor cores with a high level of fidelity would make the method viable for core diagnostics in power reactors.

Although the estimation of a power reactor transfer function is a far from trivial task, some earlier work demonstrated that its estimation for actual heterogeneous reactor configurations has many advantages from a noise diagnostic viewpoint. Capitalizing on recent advancements in reactor transfer estimation, an application to Horizon 2020 (in the 2016-2017 Euratom work Program) was prepared and submitted in late 2016, and approved for funding in early 2017. The project, called CORTEX (with CORTEX standing for CORE monitoring Techniques and EXperimental validation

and demonstration), is a Research and Innovation Action financed by the European Union. The project formally started on September 1st, 2017 for a duration of four years.

The purpose of this paper is to present the concept on which the project relies and to give an overview of the corresponding key features.

2. Project concept and key features

While advanced signal analysis methods can be utilized to detect anomalous patterns from the recorded fluctuations throughout the core, a promising but challenging application of core diagnostics consists in using the readings of the (usually very few) detectors (out-of-core neutron counters, in-core power/flux monitors, thermocouples, pressure transducers, etc.), located inside the core and/or at its periphery, to backtrack the nature and spatial distribution of the anomaly that gives rise to the recorded fluctuations.

Although intelligent signal processing techniques could also be of help for such a purpose, they would generally not be sufficient by themselves. Therefore, a more comprehensive solution strategy is adopted in CORTEX and relies, as earlier indicated, on the determination of the reactor transfer function. The transfer function gives the response throughout the entire system of the neutron flux induced by a known distribution of perturbations. If the perturbations reduce to a Dirac function with respect to space, the transfer function corresponds to the Green's function of the reactor. Once the reactor transfer function has been determined, inverting this function and applying it to the recorded signals allows – in principle – retrieving some information about the initiating perturbation. Subsequently, the possible impact of the identified anomaly on reactor safety and operation can be assessed.

The overall concept used in CORTEX is thus based on the inversion of the reactor transfer function after adequate processing of the signals, as depicted in Figure 2.

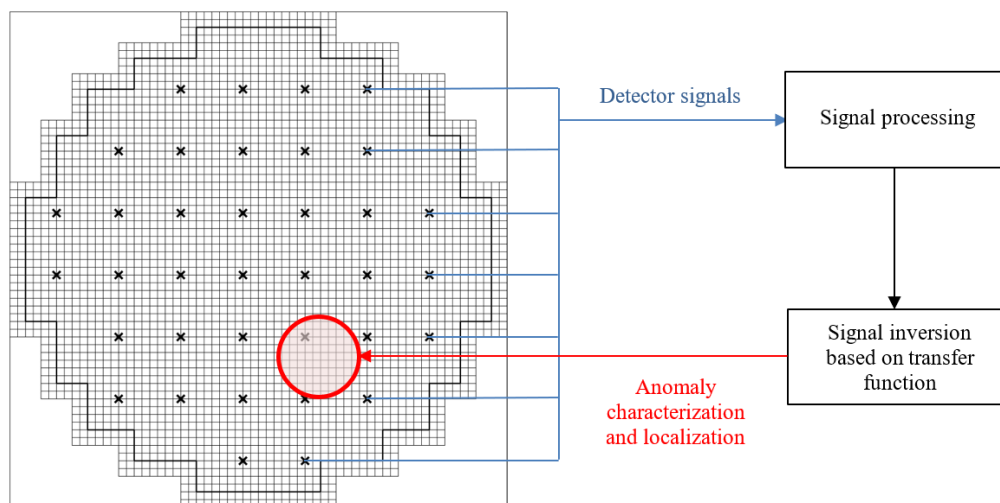


Figure 2 Conceptual illustration of the concept of CORTEX. The left-hand figure represents the radial layout of a LWR (in the present case, a Boiling Water Reactor – BWR) with fuel assemblies as squares and detector strings as crosses. The project aims, among other things, at identifying regions of the core (conceptually highlighted in red) where a possible anomaly is located.

The origin of the fluctuations from the measured signals (unfolding) can only be retrieved if the reactor transfer function is (a) perfectly known and (b) can be inverted.

Regarding point (a), the project aims at further developing the existing capabilities for estimating the reactor transfer function, to capitalize on those, and to develop new methods. Because high-fidelity methods will be developed, their validation is of utmost importance and will represent an essential part of the project. Two zero-power facilities will be used to design noise-dedicated experiments: the CROCUS reactor at l'Ecole Polytechnique Fédérale de Lausanne (Switzerland) and the AKR-2 reactor at the Technische Universität Dresden (Germany).

Concerning point (b), the inversion of the reactor function is only possible if the induced neutron noise could be measured at every position inside the reactor core. Since western type LWRs have only limited in-core instrumentation, one of the challenges of analyzing plant data is the scarcity of in-core measurement points. Advanced signal processing techniques and artificial/computational intelligence methodologies (artificial neural networks, machine learning techniques, fuzzy logic) combined with advanced interpolation methods have been found capable of circumventing those difficulties for performing an inversion of the reactor transfer function. Additionally, some processes are not stationary but rather intermittent, in which case traditional frequency analysis is far from effective. Such processes can be successfully handled by wavelet-based analysis.

When developed, a large part of the project will be dedicated to the application of the new methodology to commercial nuclear power stations.

3. Conclusion

The CORTEX project, briefly described in this paper, aims at developing core monitoring techniques allowing the early identification, characterization, and localization of possible anomalies, before those have any inadvertent effects on plant availability and safety. This will be achieved by combining numerically-estimated reactor transfer functions with machine learning techniques in order to unfold possible anomalies from the neutron noise measured by the available core instrumentation.

The ambition with CORTEX is to develop a technique directly usable by the industry. This technique will be applicable to both the existing fleet of reactors and to the reactors to be built. Although the demonstrations will be carried out on Gen-II thermal reactors, the principles and concepts developed in CORTEX will also be valid for Gen-III and Gen-IV reactors.

With the overall ageing fleet of nuclear reactors worldwide, operational problems are anticipated to become more frequent. Therefore, the results of this project will also serve Technical Support Organizations and regulatory bodies in the assessment of possible safety impacts of such events.

4. Acknowledgments

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