OVERVIEW OF THE CORTEX PROJECT

Demazière C[1], Vinai P[1], Hursin M[2], Kollias S[3], and Herb J[4]

[1]Chalmers University of Technology
Department of Physics, Division of Subatomic and Plasma Physics
SE-412 96 Gothenburg, Sweden

[2]Ecole Polytechnique Fédérale De Lausanne
Ecole Polytechnique Federale de Lausanne (EPFL)
1015 Lausanne, Switzerland

[3]University of Lincoln
Lincoln
Brayford Pool
LN6 7TS, United Kingdom

[4]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Forschungszentrum
Boltzmannstraße 14
85748 Garching b. München, Germany

demaz@chalmers.se, vinai@chalmers.se, mathieu.hursin@epfl.ch, skollias@lincoln.ac.uk, joachim.herb@grs.de

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. In order to develop a method that can reach a high Technology Readiness Level, the consortium, made of 20 partners, was strategically structured around the required core expertise from all the necessary actors of the nuclear industry, both within Europe and outside. The broad expertise of the consortium members ensures the successful development of new in-situ monitoring techniques.

KEYWORDS: core monitoring and diagnostics, noise analysis, reactor modelling, validation, signal processing, machine learning

1. INTRODUCTION

One of the crucial aspects for the safe and reliable operation of nuclear power plants is the monitoring of the instantaneous state of the reactors, so that possible anomalies can be detected early on and proper actions can be promptly taken. In the future, this will represent an increasingly important challenge for several reasons. On the one hand, over 60% of the current fleet of nuclear reactors is composed of units more than 30 years old, therefore operational problems are expected to be more frequent. On the other hand, the conservatism previously applied to the evaluation of safety parameters has been greatly reduced, thanks to the increased level of fidelity achieved by the current tools modelling the behavior of nuclear reactors. As a result, nuclear reactors are now operating more closely to their safety limits. Operational problems may be also accentuated by other factors, such as the use of advanced high-burnup fuel designs and core loadings.

Being able to monitor the state of reactors while they are running at nominal conditions would be extremely advantageous. The early detection of anomalies would give 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:

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

where $X\left(\mathbf{r},t\right)$ is the actual signal and $X_0\left(\mathbf{r},t\right)$ is the signal trend (usually obtained after filtering the original signal). This is conceptually illustrated in Fig. 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 [1]. 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.

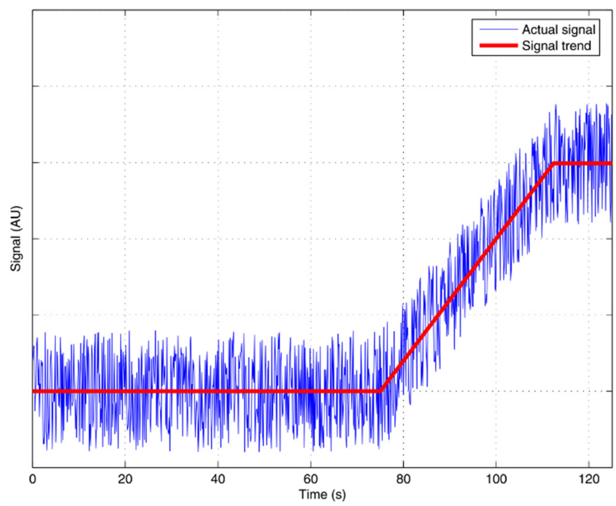

Fig. 1. Conceptual illustration of the fluctuations observed in process parameter measurements. The fluctuations are defined as the deviation of the actual signal from its trend.

The principles of neutron noise analysis were already established in the early days of the development of nuclear power, with oscillator experiments carried out in the Clinton Pile at the Oak Ridge National Laboratory (TN, USA) for measuring nuclear cross-sections. It was then observed that the response in neutron flux corresponding to a local but stationary excitation of the system had a spatial dependence deviating from point-kinetics. A so-called local component of the neutron fluctuations could be noticed near the applied perturbation, with such a component having a much larger amplitude than the global component [2]. Later, excessive vibrations of control rods in the Oak Ridge Research Reactor and the High Flux Isotope Reactor could be detected [3].

This is how the concept of noise analysis, i.e. using the inherent fluctuations in primarily the neutron flux to recover some information about the state of the system, was born. The first applications in commercial reactors included the detection of core-barrel vibrations at the Palisades plant, USA [4] and the estimation of in-core coolant velocity in German Boiling Water Reactors (BWRs) [5].

The area of neutron noise analysis and core diagnostics was most prolific during the 1970s and 1980s, as can be noticed by the vast literature then published. Despite the large amount of research performed and published, there are only very few cases where noise analysis is used on a routine basis in support to plant operations: one could refer to the PAZAR reactor noise data acquisition and evaluation system [6] and the VERONA core monitoring system [7], both at the Paks nuclear power plant in Hungary, as well as the diagnostics tools system at the Czech nuclear power plants [8].

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 signals [e.g. 9, 10, 11, 12, 13]. 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 [14]. Capitalizing on recent advancements in reactor transfer estimation [see e.g. 15, 16, 17, 18, 19, 20], 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, to give an overview of the corresponding key features and to briefly introduce the cross-disciplinary expertise of the consortium.

2. PROJECT CONCEPT

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. For the sake of simplicity and illustration, the transfer function, also referred to as the *Green's function*, will be denoted hereafter as $G\left(\mathbf{r},\mathbf{r}_{\mathrm{p}},\omega\right)$, where $\mathbf{r}_{\mathrm{p}}$ represents the position of an assumed perturbation of a parameter P and $\mathbf{r}$ is the position at which the effect of the perturbation applied to the system is measured. The transfer function depends on the angular frequency ω of the applied perturbation. Fig. 2 gives a conceptual illustration of the reactor transfer function relating the perturbation $\delta P\left(\mathbf{r}_{\mathrm{p}},\omega\right)$, which in the most general case also depends on the frequency, to the induced fluctuations in neutron flux $\delta\phi\left(\mathbf{r},\omega\right)$.

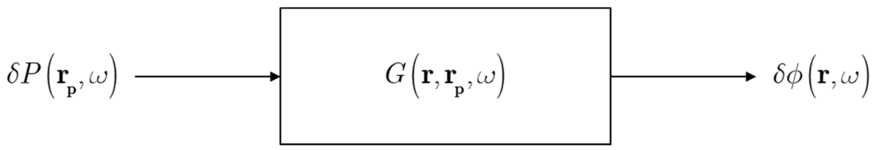

Fig. 2. Conceptual illustration of the reactor transfer function.

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, as depicted in Fig. 3. Subsequently, the possible impact of the identified anomaly on reactor safety and operation can be assessed.

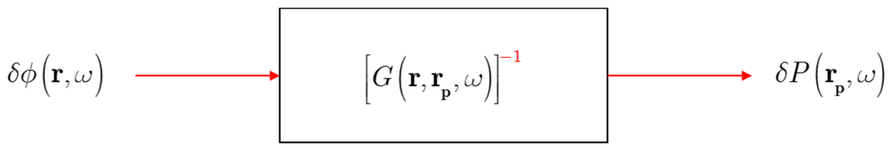

Fig. 3. Conceptual illustration of the inversion of the reactor transfer function.

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 Fig. 4.

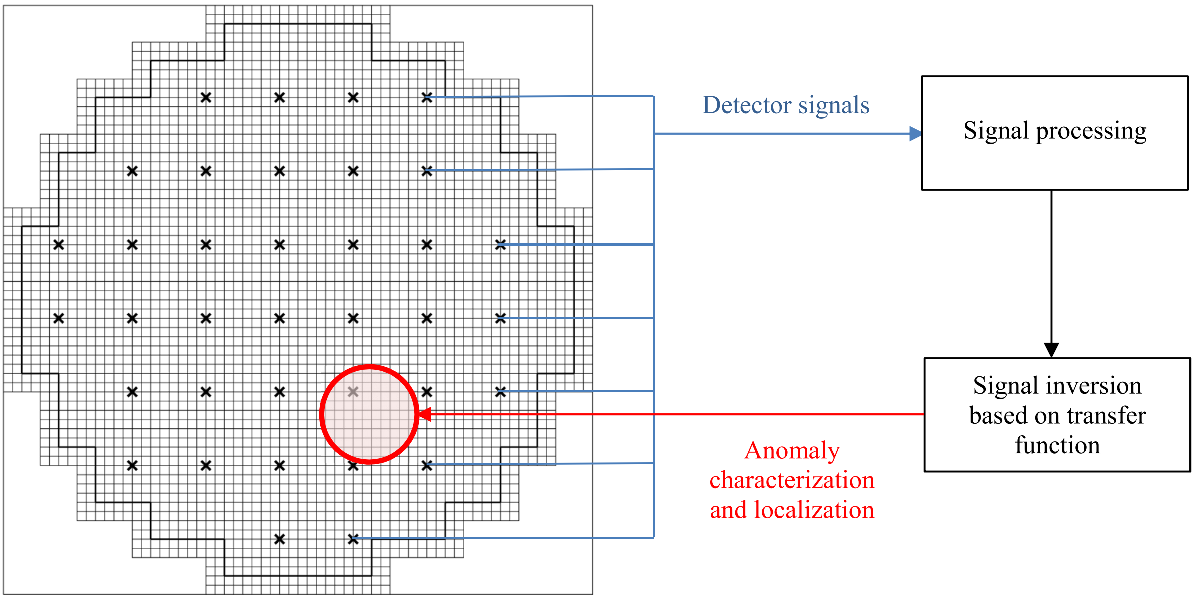

Fig. 4. Conceptual illustration of the concept of CORTEX. The left-hand figure represents the radial layout of a LWR (in the present case, a Boiling Water Reactor – BWR) with fuel assemblies as squares and detector strings as crosses. The project aims, among other things, at identifying regions of the core (conceptually highlighted in red) where a possible anomaly is located.

3. PROJECT KEY FEATURES

Although conceptually simple, 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. The uncertainty associated to the calculated transfer function will be assessed, as well as the sensitivity of the estimated function to input parameters. In our case, emphasis will be put on the open-loop reactor transfer function, i.e. the transfer function that relates perturbations expressed as fluctuations of macroscopic cross-sections to the induced fluctuations in the neutron density field. The incentive is to develop high-fidelity methods that can be used by the industry. Such methods will thus rely on neutron transport, either deterministic or probabilistic. Diffusion theory will also be used in order to provide a fast-running alternative on which signal processing algorithms can be developed and tested, prior to be applied onto neutron transport-based transfer functions to be developed during the course of the project. In addition, by comparing the transport and diffusion-based methods, the project will also point out when the use of diffusion theory is sufficient.

The specification of the noise sources will be given particular attention when estimating the reactor transfer function. The driving perturbations will be either directly expressed as fluctuations of the macroscopic cross-sections using expert opinion or given in more physical terms. For the latter case, emphasis will be put on mechanical vibrations, Fluid-Structure Interactions (FSIs), and their effect on macroscopic cross-sections and neutron fluxes.

Since the project aims at developing high-fidelity methods, 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). Different types of perturbations are planned to be investigated: an absorber of variable strength (directly corresponding to the Green's function) and a vibrating absorber (corresponding to the derivative of the Green's function with respect to the equilibrium position of the absorber). New types of detectors will be investigated and tested, so that not only the scalar neutron flux can be measured but also the neutron current. Recovering some higher moments of the neutron angular flux gives extra information about the gradient of the neutron density field, which itself is of value when trying to estimate the position of an unknown perturbation.

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 combined with advanced interpolation methods have been found capable of circumventing this difficulty. The application of such techniques will thus be considered in the project.

Furthermore, in the computational part of the procedure, the direct task of calculating the induced noise from a known perturbation using the calculated transfer function can only be solved numerically. Hence, no theoretical or analytical inversion is available for extracting the noise source parameters from the measured noise. Non-parametric inversion methods, such as artificial neural networks which can predict the value or classes of parameters of interest, machine learning algorithms which can maximize the agreement between observed and reconstructed data and fuzzy logic which can represent data in a robust manner, represent powerful new tools for solving such problems. Of specific interest are deep neural networks which can handle complex time and space varying data. Those networks currently constitute the state-of-the-art in the analysis of complex data in the fields of speech analysis, vision and natural language processing [21, 22, 23].

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.

It should be mentioned that the above techniques exhibit robustness to parasitic noise, missing values, and non-linearities, all of which are inherent in the recorded data.

Finally, and most importantly, a large part of the project is dedicated to the application of the new methodology (being developed within the project) to commercial nuclear power stations. The data to be used for demonstrating the applicability, usefulness, and importance to the nuclear industry of the methodology will come from several reactor types: a pre-KONVOI 3-loop PWR, a pre-KONVOI 4-loop PWR, a VVER 440 reactor, a VVER 1000 reactor, two 4-loop PWRs and one 3-loop PWR. Some data (either simulated or coming from actual measurements) with known "anomalies" will allow testing the applicability of the method.

The structure of the project is thus based on four technical work packages that can be summarized as follows:

1. The estimation of the reactor transfer function.
2. Its validation against noise-specific measurements in research reactors.
3. The development of adequate signal processing and inversion techniques using the estimated reactor transfer functions.
4. The demonstration of the method on actual plant data.

4. PROJECT CONSORTIUM

Cross-disciplinary expertise in reactor modelling, neutron transport, thermal-hydraulics, structural mechanics, experimental techniques, signal analysis and processing, measurement techniques and in the analysis of plant data is thus necessary for the successful development of the concepts highlighted above. The consortium gathered in CORTEX covers all these disciplines, with experts from academia, research institutes, Technical Safety/Support Organizations (TSOs), regulators, private companies and utilities. A particular attention is given to the end-users, who are either directly contributing to the project by providing data and expertise or by participating to the consultative body of the consortium.

The project is coordinated by Chalmers University of Technology, Sweden. Chalmers is one of the leading groups in noise analysis and core diagnostics, with expertise developed in those areas since the mid-1990s. The project consortium consists in total of 20 partners. The partners are listed in Table I together with their respective short names and expertise areas.

Table I. List of the consortium partners per country, with their respective expertise areas (1 – reactor transfer function estimation, 2 – noise-specific measurements in research reactors, 3 – signal processing and inversion techniques, 4 – demonstration on actual plant data).

Country	Consortium partner	Expertise			
		1	2	3	4
Sweden	Chalmers Tekniska Hoegskola AB – Chalmers	●	●	●	●
Germany	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH – GRS	●			●
	TUV Rheinland ISTec GmbH - Institut fur Sicherheitstechnologie – ISTec		●		●
	TUV Rheinland Industrie Service GmbH – TIS		●		●
	Technische Universität Dresden – TUD	●	●		
	Technische Universitaet Muenchen – TUM	●			
	PreussenElektra GmbH – PEL				●
Switzerland	Ecole Polytechnique Fédérale de Lausanne – EPFL		●		
	Paul Scherrer Institute – PSI	●	●	●	●
	Kernkraftwerk Gösgen-Däniken AG – KKG				●
Spain	Universidad Politécnica de Madrid – UPM			●	●
	Universitat Politecnica de Valencia – UPV	●	●		
France	Commissariat à l'Energie Atomique et aux énergies alternatives – CEA	●	●	●	●
	LGI Consulting – LGI	(project management)			
United Kingdom	University of Lincoln – UoL			●	●
Greece	Institute of Communication & Computer Systems –National Technical University of Athens – ICCS-NTUA			●	●
Hungary	Magyar Tudomanyos Akedemia Energiatudomanyi Kutatokozpont – MTA EK			●	●
Czech Republic	UJV Rez, a. s. – UJV			●	●
Japan	National University Corporation, Kyoto University – KU	●			
USA	Analysis and Measurement Services Corporation – AMS				●

Five additional organizations are involved in CORTEX, by participating to a consultative body, called the Advisory End-User Group (AEUG). The AEUG allows to integrate comments and feedback on the on-going activities in CORTEX, in order to align the project to potential end-users' needs. The complete list of the members of the AEUG is given below:

- IRSN (France).
- KKG (Switzerland).
- PEL (Germany).
- Ringhals (Sweden).
- Tractebel (Belgium).
- CNAT (Spain).
- AREVA (Germany).
- Westinghouse Electric Sweden AB (Sweden).

The consortium is composed of five European private companies (ISTec, TIS, KKG, UJV, PEL), one European Small and medium-Sized Enterprise – SME – (LGI), four European research organizations (CEA, GRS, MTA EK, PSI), eight European universities (Chalmers, EPFL, ICCS-NTUA, TUD, TUM, UPM, UPV, UoL), as well as one Japanese university (KU) and one American SME (AMS).

The interest of the industry in this project is shown further by the presence of companies such as CNAT, Tractebel, Ringhals AB (a subsidiary of Vattenfall), AREVA and Westinghouse Electric Sweden AB in the AEUG. A Technical Support Organization (IRSN) also participates to the AEUG. The perspectives of the utilities will also be continuously included in the project via the presence in the consortium of two end-users (KKG and PEL). Beyond contributing with data and their expertise, these two end-users will allow keeping the project focused on the needs of the industry.

The academic partners (Chalmers, EPFL, ICCS-NTUA, TUD, TUM, UPM, UPV, UoL) contribute to the project by capitalizing on the knowledge and expertise in their respective areas of research (as highlighted in Table I), in order to develop beyond state-of-the-art methods. The research institutes (CEA, GRS, PSI), in addition to developing such methods, ensure the relevance of the project outcomes to potential end-users, thanks to the tight collaboration the research institutes have with industrial partners and regulatory bodies.

The consortium involves partners (ISTec, TIS and AMS) providing services to the nuclear industry on a commercial basis, as well as partners (MTA EK and UJV) who developed core monitoring techniques for commercial reactors. The involvement of such partners is essential to create a direct link between the consortium and the possible end-users of the methods. The experience of ISTec, TIS and AMS with industrial partners is an important asset to the project for incorporating end-users' expectations and feedback into the consortium.

5. CONCLUSIONS

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. This is becoming evident in some of the pre-KONVOI PWRs operating in Europe, where an increase of the amplitude of the fluctuations in neutron flux was recorded with consequences for the availability of the plants. For instance, in Germany, the reactor limitation system was activated at several occasions because of too high neutron flux levels and even led to a reactor SCRAM in at least one occurrence [24]. In Spain, the utility operating the Trillo nuclear power plant had to operate the reactor at reduced power (down to 93% of the nominal power level) at many occasions [25, 26]. To this day, the reasons of the operational problems mentioned above remain not fully understood [27]. Therefore, the results of this project will also serve TSOs and regulatory bodies in the assessment of possible safety impacts of such events.

These examples also highlight the need to develop, implement and test core monitoring and analyzing techniques before operational problems arise.

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