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Noise Analysis Techniques Of In-core Modulation Experiments For The European Project CORTEX

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ABSTRACT

This paper deals with the analysis of reactor modulation experiments for code validation in the framework of the Horizon 2020 European project CORTEX. The analysis is based on a statistical based approach on spectral powers and their phase shift angles calculations. The treatment of individual oscillations as independent aids in elimination of possible biases and correlations of consecutive oscillations. Results from one of the experimental campaign performed at the AKR-2 and CROCUS reactors are also presented.

1 INTRODUCTION

The European project CORTEX project [1] aims to develop core monitoring techniques for identifying reactor noise sources and their location inside the reactor core, coming from oscillating fuel rods, boiling and numerous other oscillatory perturbations, which effect the neutron field. More specifically the tasks of the Work package 2 (WP2) validation of computational codes for predicting the modulations by experiments. The experiments were performed at

two reactors, equipped with neutron field modulators and numerous distributed detectors. The quantities of interest (QOI) for code validation are spectral power (PS) and phase shift angle between detector pairs. For normalization purposes, PS ratios to a reference detector set and phase shifts in relation to a reference detector are calculated.
In order to extract high quality QOI from the experimental data, a set of analysis scripts were developed. These are based on statistical resampling of detector and oscillator position datasets using Bootstrapping with replacement with individual oscillations as representative subsamples. This methodology is able to identify possible biases and eliminates any possible temporal correlations between individual oscillations [2, 3].
Experiments at the Techniche Universität Dresden (TUD) Ausbildungskernreaktor 2 (AKR-2) reactor and the experimental campaign at the École Polytechnique Fédérale de Lausanne (EPFL) CROCUS reactor are briefly presented. A detailed description of the analysis techniques is presented, followed by a presentation of final results for a selected experiment in CROCUS reactor. The paper is concluded by a discussion and future outlooks.

2 EXPERIMENTS AT TUD AKR-2 AND EPFL CROCUS REACTORS

Experimental campaigns were performed at zero power research reactors which are capable of inducing neutron field modulation by various oscillators. A detailed description of the experimental campaigns is provided in [4, 5, 6]. In both cases, measurements were performed by numerous detectors in and around the reactor core. Three separate data acquisition (DAQ) systems were used namely ISTec , EPFL and TUD.

- The TUD AKR-2 reactor core consists of uranium loaded polyethylene discs, which are joined together during operation. The reactivity is controlled via neutron absorber control rods. The reactor is also equipped with two different types of neutron oscillators in the form of moving absorbers: a variable strength absorber with rotating movement (Figure 5a) and a vibrating absorber (linear actuation) (Figure 5b). The detector and oscillating absorber positions during are schematically displayed in Figure 2.

(a) Absorber of variable strengths.

(b) Vibrating absorber.

Figure 1: Oscillator assemblies mounted on the TUD AKR-2 reactor casing.

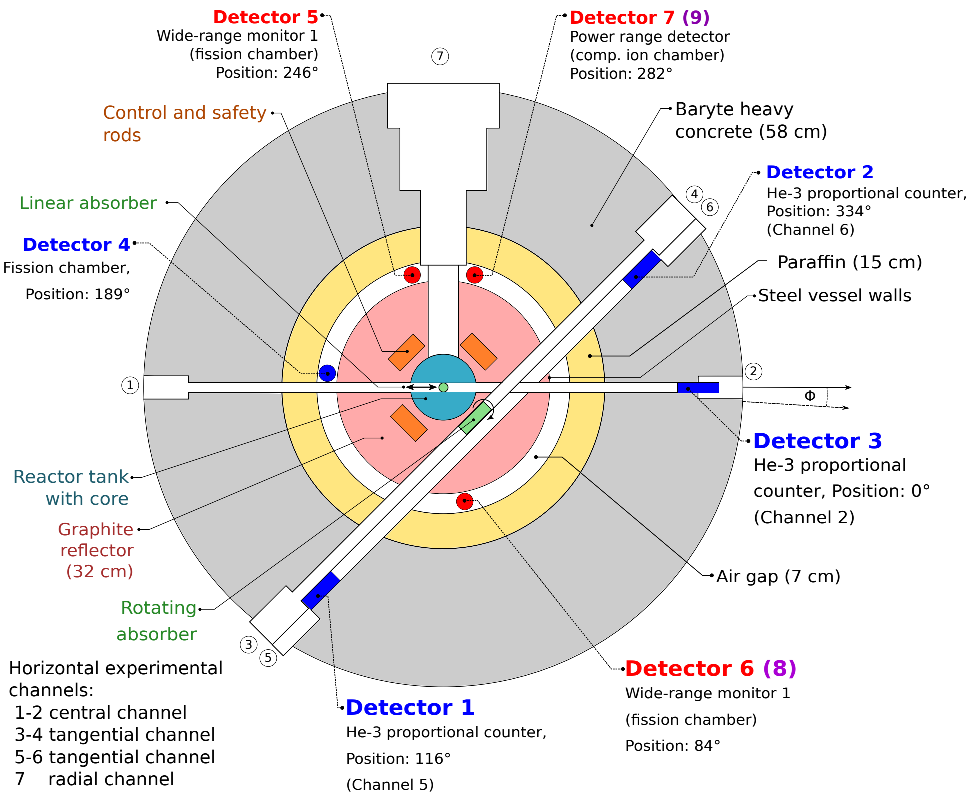


Figure 2: TUD AKR-2 schematic during the experimental campaign. Detector numbers in violet denote an additional measurement chain from the same detector.

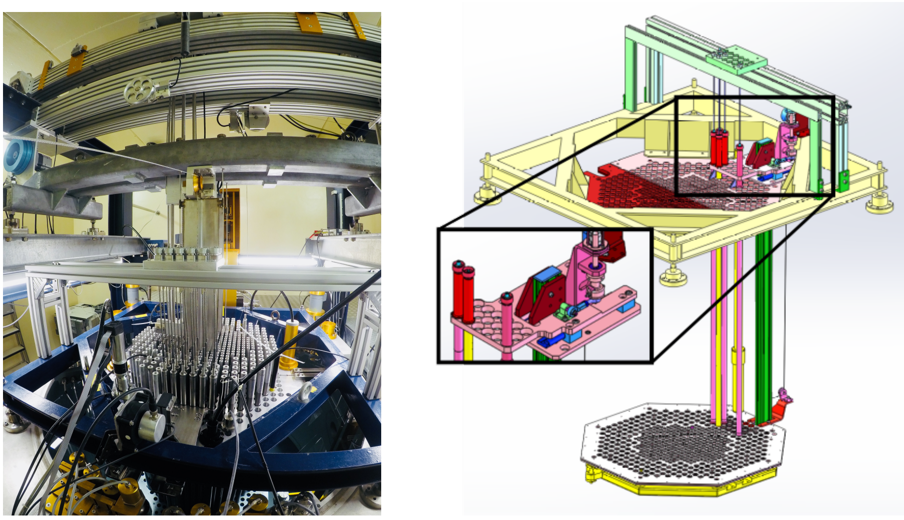
- The EPFL CROCUS reactor (Figure 3a) is a pool-type zero power nuclear reactor, where the reactivity is controlled by adjusting the pool water level or by two boron carbide control rods. The reactor has two interlocking fuel zones: inner and outer fuel zone, each comprising of a different fuel type and different pitch. The fuel oscillation experiment called COLIBRI (Figure 3b) is located at the edge of the reactor. It has the capability to oscillate up to 18 fuel elements with a frequency of up to $2\,\mathrm{Hz}$ and amplitude of up to $\pm 2.5\,\mathrm{mm}$.
  The detector positions during the first experimental campaign are schematically displayed in Figure 4.

3 NOVEL ANALYSIS TECHNIQUES

When dealing with spectral analysis of noise or induced oscillations, the intermediate quantities of interest are power spectral density (PSD) and the PSD derived phase angle of two signals, showing their spectral density relation and phase shift between them. The PSD between signals i and j is defined as the average of periodograms (PER) between same respective signals, which is defined by Equation 1:

$$PER_{i,j}(\upsilon) = X_i(\upsilon)^* \cdot X_j(\upsilon) = FFT(x_i(t))^* \cdot FFT(x_j(t)) \tag{1}$$

where $X_i(\upsilon)$ and $X_j(\upsilon)$ are frequency domain Fourier transforms of temporal signals x_i and x_j



(a) Reactor with COLIBRI experiment in front.

(b) CAD drawing of the COLIBRI experiment

Figure 3: Pictures of EPFL CROCUS reactor and the COLIBRI experiment.

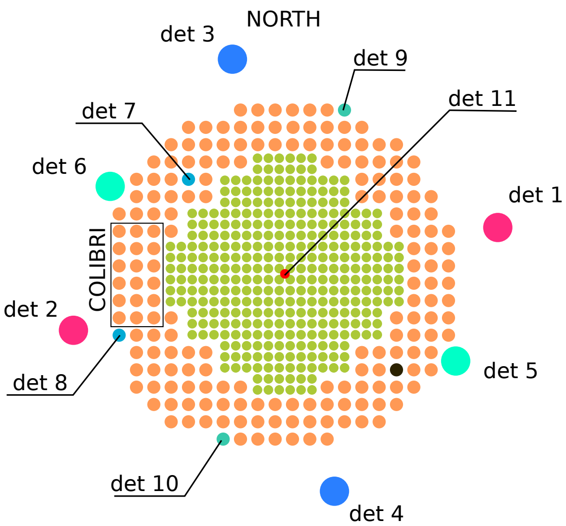


Figure 4: CROCUS schematic and detector positions during the first CORTEX experimental campaign. Inner fuel zone in green, outer fuel zone in orange and a single control rod in black.

from detectors i and j respectively. The PSD derivation is described by Equation 2:

$$PSD_{i,j}(\upsilon) = \frac{\sum_{k=1}^{N} PER_{k,i,j}(\upsilon)}{N} \tag{2}$$

The established way of calculating a PSD is by selecting signal sections of equal size without or with overlap (and appropriately weighted) for PER calculations.
Calculation of the phase angle $\phi_{i,j}$ between signals i and j is described in Equation 3.

$$\phi_{i,j}(\upsilon) = arg(PSD_{i,j}(\upsilon)) \tag{3}$$

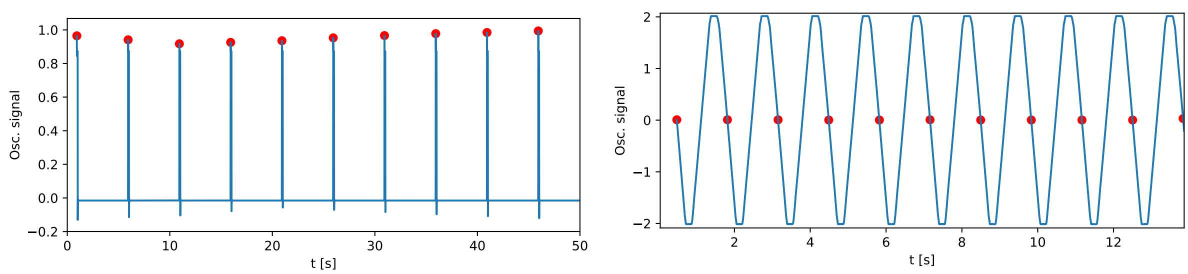
Another useful quantity describing the relation i.e. the power transfer between signal i and signal j is known as coherence $COH_{i,j}$, defined by Equation 4.

$$COH_{i,j}(\upsilon) = \frac{abs(PSD_{i,j}(\upsilon))^2}{real(PSD_{i,i}(\upsilon)) \cdot real(PSD_{j,j}(\upsilon))} \tag{4}$$

In practice, this acts as an indicator of the data quality: one aims for the $COH > 0.8$.
Most commonly the Welch windowing method is used [7] for PSD calculations, which induces spectral effects similar to band-pass filters [8]. Due to using shorter original signals, the frequency resolution of the resulting Fourier transform drops as well. The correlations between consecutive oscillations and biases present in sections of the signal also affect the analysis.
The analysis results will be used for code validation using simulating stationary oscillations. It is therefore of utmost importance to eliminate any additional changes to the spectral response, and to treat measurement data as a collection of individual oscillations, without making any assumptions. The methodology discussed in [2, 3] proposes resampling of the original data from a pool of representative sub-samples, reconstructing a new data series with $\approx M^M$ different possibilities (where M is a number of subsections). Fourier transform of the resampled data is used to obtain the modified PER. Using a large number of resampled data, the mean value and the standard deviation converge and can be easily calculated. This resampling methodology is used in this work to obtain PSD, phase angle ϕ and COH with detector signals during individual oscillations as representative subsamples. The aim of this analysis is to identify the PSD spectral peaks at the base or higher harmonic frequencies of the induced perturbation frequency i.e. calculating the spectral power $PS_{i,j,l}$ which is the area under the $PSD_{i,j}$ peak l. In case of arbitrary normalization and detector signal standardization PS to a reference detector's (R) base frequency $\frac{PS_{i,j,k}}{PS_{i,R,0}}$ and a harmonic of the same order $\frac{PS_{i,j,k}}{PS_{i,R,k}}$ are calculated. Same goes for the phase angles $\phi_{i,j,l}$, except instead of the ratios ratio, differences in phase shifts are calculated. The two above mentioned quantities: PS ratios and phase shift differences are the main QOI for the computer code validation.

3.1 Resampling

We want to eliminate temporal correlations between representative subsamples and treat individual oscillations as independent. Therefore detector responses to individual oscillations are our representative sub-samples. Well defined oscillation boundaries have to be defined for signal sectioning. In case of the TUD AKR-2 oscillators, a single pulse per cycle is given for the variable strength absorber, while the position of the vibrating absorber is logged continuously. For distinguishing between individual oscillations, local maxima are selected for the variable strength absorber, while zero-crossings are selected for the vibrating/linear absorber (Figure 5). For the CROCUS reactor Colibri oscillator, zero-crossings were selected for distinguishing between individual oscillations (Figure 6). Based on these reference points, the original signal



(a) Variable strength absorber signal and reference points at $0.2\,\text{Hz}$.

(b) Vibrating absorber signal and reference points at $0.714\,\text{Hz}$.

Figure 5: Absorber signal, both at $0.2\,\text{Hz}$ and the reference points for distinguishing between individual oscillations.

was split by individual oscillations and resampled as shown in Figure 7.

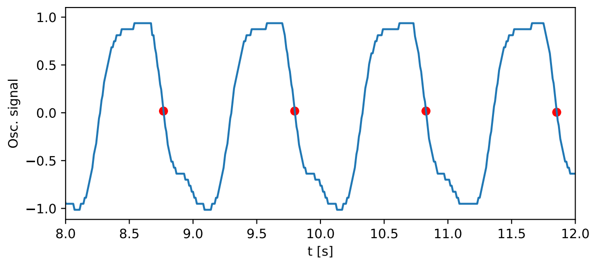


Figure 6: CROCUS Colibri position signal at amplitude of $1.5\,\mathrm{mm}$ and oscillation frequency of $0.97\,\mathrm{Hz}$.

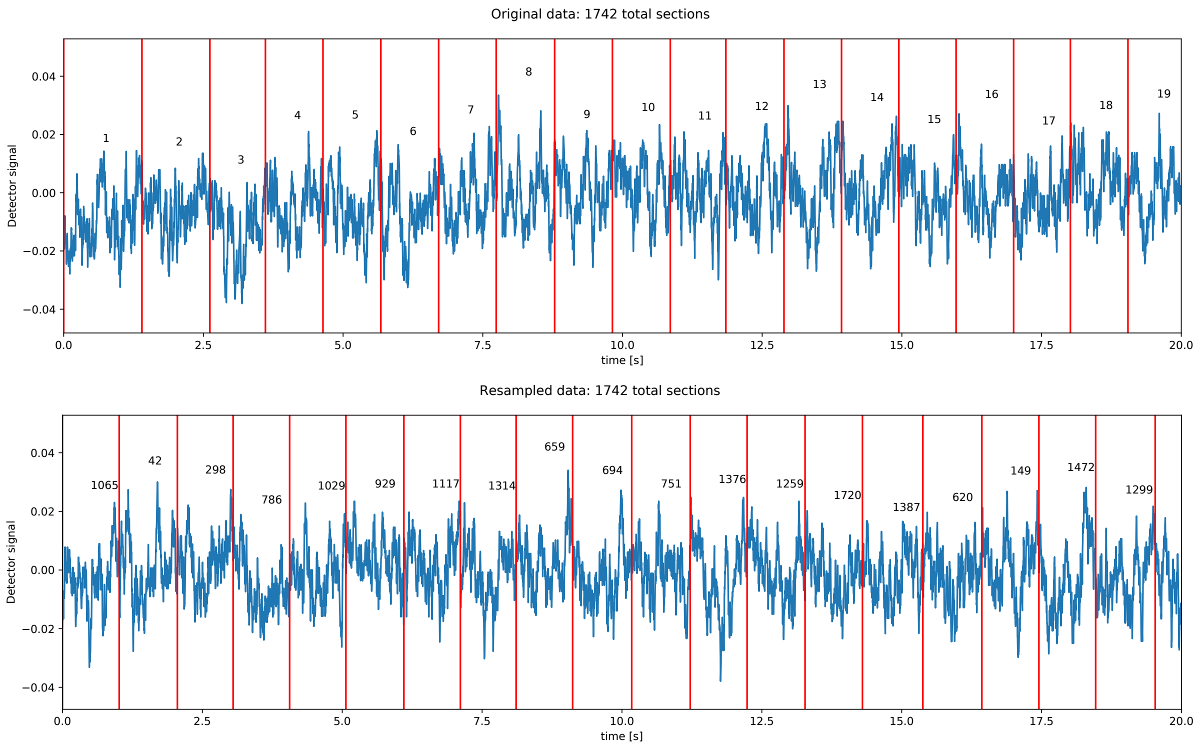
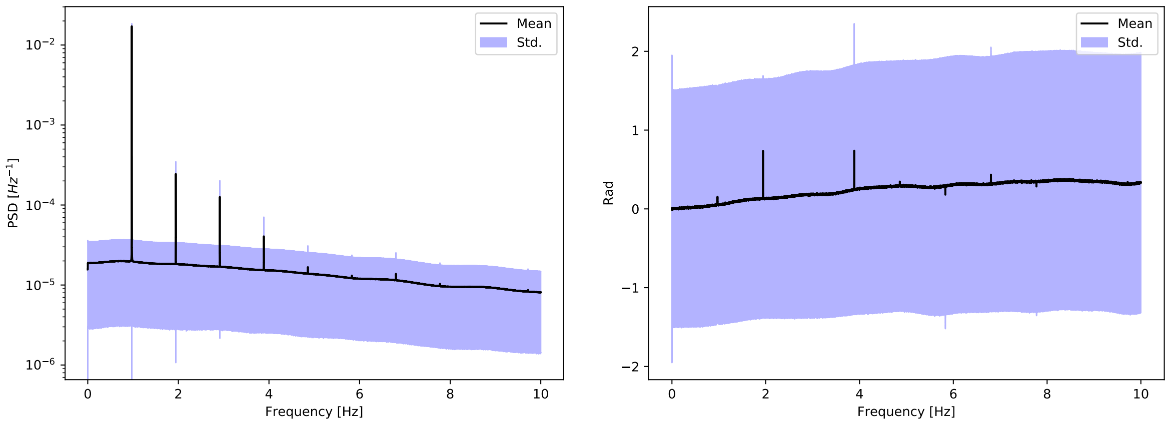


Figure 7: An example of original and resampled detector signal.

4 RESULTS

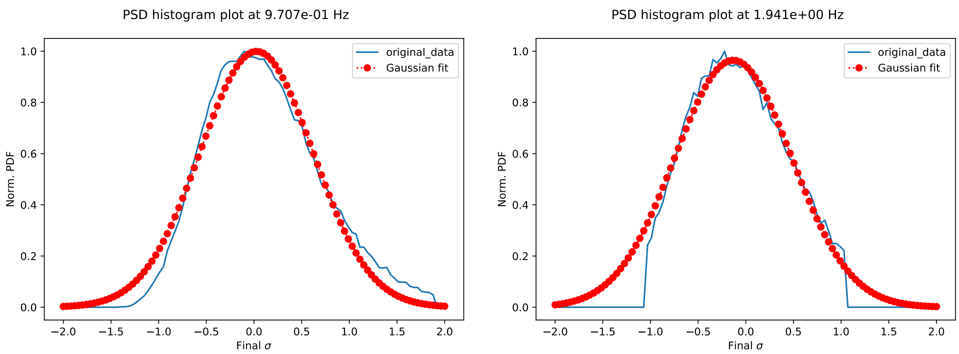
The QOI are frequency dependent PSD and phase angle ϕ mean values and their uncertainties, displayed in Figure 8, with clearly distinguishable base and higher harmonic frequency peaks. The PSD distributions of base and 1st harmonic frequency averaged data over 10 samples along with fitted Gaussian distributions for comparison purposes are displayed in Figure 9. For validation purposes we use relative values of QOI with respect to a chose detector. The PS and ϕ uncertainties can be easily calculated from obtained distributions. The ratios represent the detected spectral power with respect to the reference combination. Because of the provided uncertainties, weighted mean and weighted relative standard deviation can be calculated, as displayed in Figure 10.



(a) PSD mean and uncertainty.

(b) Phase angle mean and uncertainty.

Figure 8: Intermediate results of PSD and phase angle ϕ between detectors 3 and 5 in CROCUS reactor at oscillator frequency of $0.97\,\mathrm{Hz}$ and amplitude of $1.6\,\mathrm{mm}$.



(a) Base PSD peak distribution.

(b) 1st harmonic PSD distribution-

Figure 9: PSD distributions of base and 1st harmonic peaks between detectors 3 and 5 in CROCUS reactor at oscillator frequency of $0.97\,\mathrm{Hz}$ and amplitude of $1.6\,\mathrm{mm}$.

5 CONCLUSIONS AND OUTLOOKS

A spectral analysis has been performed, based on a non-standard derivation of power spectral densities, phase angles and coherences using bootstrapping with replacement. This aims to identify and eliminate biases, temporal correlations and windowing effects by treating each oscillation individually. Checks have been implemented to confirm the validity of the analysis approach by tallying the distributions of QOI. Spectral power ratios and phase angle estimates with uncertainties are provided to the code developers for validation in the framework of the H2020 CORTEX project.
A full core mapping of CROCUS reactor is planned for the near future where in excess of 150 detectors will be used and a similar kind of analysis will be performed.

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Figure 10: PS ratios to reference detector 5 at base frequency for the experiment No. 3 at CROCUS reactor at $0.97\,\mathrm{Hz}$ and amplitude of ± 1.6 .

REFERENCES

[1] Christophe Demazière, Paolo Vinai, et al. Overview of the CORTEX project. In *Proceedings of Physor 2018*, April 2018.

[2] Efstathios Paparoditis. *Frequency Domain Bootstrap for Time Series*, pages 365–381. Birkhäuser Boston, Boston, MA, 2002.

[3] Dragan Radulović. *On the Bootstrap and Empirical Processes for Dependent Sequences*, pages 345–364. Birkhäuser Boston, Boston, MA, 2002.

[4] Vincent Lamirand, Mathieu Hursin, et al. Experimental report on the 1st campaign at akr-2 and crocus. Technical report, Horizon 2020 Cortex, 2018.

[5] Vincent Lamirand, Adolfo Rais, et al. Neutron noise experiments in the AKR-2 and CROCUS reactors for the european project CORTEX. *EPJ Web Conf.*, 225:04023, 2020.

[6] Vincent Lamirand, Adolfo Rais, et al. Analysis of the first COLIBRI fuel rod oscillation campaign in the CROCUS reactor for the european project CORTEX. In *Proceedings of Physor 2020*, 2020.

[7] P. Welch. The use of fast fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *IEEE Transactions on Audio and Electroacoustics*, 15(2):70–73, 1967.

[8] O. M. Solomon. The effects of windowing and quantization error on the amplitude of frequency-domain functions. *IEEE Transactions on Instrumentation and Measurement*, 41(6):932–937, 1992.