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Core Diagnostics Using Noise Analysis: From Proof-Of-Principle to Industrial Demonstration

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Abstract - *Reactor noise analysis, based upon the monitoring of the deviations of typically the neutron flux from its mean value, has for objectives a) the early detection of anomalies before they have any inadvertent effect on plant safety and availability and b) the determination of dynamical core parameters. Because noise analysis is a non-intrusive technique, it can be used on-line while the reactor is running at nominal full power conditions. One of the challenges of noise diagnostics is nevertheless to be able to recover from very few neutron detector signals the nature and characteristics of the driving perturbation, localize it, and classify the severity of the anomaly. This requires competences in many areas, such as reactor physics and dynamics, reactor modelling, stochastic processes, signal analysis, and measurement techniques. This paper represents an attempt to pay a tribute to Dr. Pázsit's seminal work on power reactor noise at the occasion of the special session organized in his honor at M&C 2017. Emphasis will be put on the development of innovative methods that resulted in industrial demonstrations at commercial nuclear power stations. The subjects covered hereafter are: the monitoring of control rod vibrations, the characterization and localization of anomalies, the diagnostics of BWR instabilities and the diagnostics of core barrel vibrations.*

I. INTRODUCTION

With the overall ageing fleet of nuclear reactors worldwide, operational problems are anticipated to become more frequent. This was recently demonstrated in some of the pre-KONVOI Pressurized Water Reactors (PWRs) in Germany, Switzerland and Spain, where an increase of the amplitude of the fluctuations in neutron flux was noticed. In some cases, the availability of the plants was affected. In Germany for instance, 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 [1]. 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 [2, 3]. To this day, the operational problems mentioned above remain unexplained [4].

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. Noise analysis, which relies on the measurement of fluctuations of process parameters (primarily the neutron flux) around their mean values, has the potential to provide non-intrusive on-line core monitoring capabilities. The 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. $\mathbf{r}$ and t represent the spatial (i.e. position) and temporal variables, 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 [5]. 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.

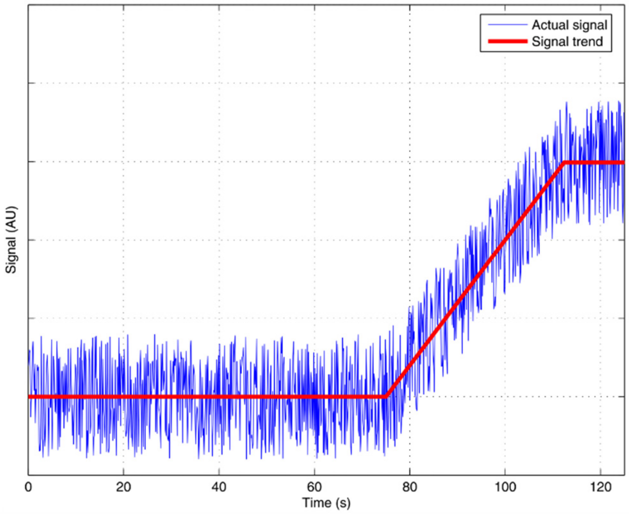


Fig. 1. Conceptual illustration of the fluctuations observed in process parameter measurements. The fluctuations are defined as the deviation of the actual signal from its trend.

One of the leading groups in noise analysis is at Chalmers University of Technology. In 1991, Dr. Imre Pázsit obtained a professorship at Chalmers and activities in this area were formally established in the mid-1990s at Chalmers, when corresponding research grants were obtained. Imre, who started working on neutron noise in the mid-1970s already, has been instrumental in the development of noise analysis techniques, ranging from theoretical models to practical applications and demonstrations at operating nuclear power plants. This paper represents an attempt to pay tribute to his seminal work in this area at the occasion of the special session organized in his honor at M&C2017.

II. EARLY DEVELOPMENT IN NOISE ANALYSIS

Already in the early days of the development of nuclear power, the principles of neutron noise analysis were established 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 [6]. Later, excessive vibrations of control rods in the Oak Ridge Research Reactor and the High Flux Isotope Reactor could be detected [7].

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 [8] and the estimation of in-core coolant velocity in German Boiling Water Reactors (BWRs) [9].

III. DR. PÁZSIT'S CONTRIBUTION TO THE FIELD

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. This is also demonstrated by the series of symposia and meetings held during the period 1974 – 2004, with SMORN-I to -VIII (Symposium On Reactor Noise and Surveillance) and IMORN-1 to -29 (Informal Meeting On Reactor Noise). Imre – who was the organizer and chairman of the last SMORN conference – extensively contributed to the research published in this area.

He obtained his PhD in nuclear and reactor physics from Roland Eötvös University in Budapest, Hungary in 1975 under the supervision of Dr. G. Kosály, one of the pioneers in neutron noise analysis. Those were times when most of the theory and possible applications of neutron noise analysis remained to be discovered, with two seminal books earlier published on the subject: Power Reactor Noise by J.A. Thie in 1963 and Random Processes in Nuclear Reactors by M.M.R. Williams in 1974. Imre visited Dr. Williams at Queen Mary College, London, UK as an IAEA research fellow in 1979. A long-standing collaboration and friendships resulted from this visit.

Imre's contributions to the area of noise analysis is too extensive to be summarized in all details. One can only pinpoint hereafter some of the main research directions followed.

1. Control Rod Vibrations

The modelling of control rod vibrations in PWRs was undertaken by Imre, together with the attempt to unfold from the neutron noise measured at a few discrete positions the location of excessively vibrating control rods (see for instance [10 - 13]). The essence of the work lies on the modelling of a vibrating control rod as fluctuations in the macroscopic cross-sections as:

$$\delta\Sigma\left(\mathbf{r},t\right)=\gamma\left[\delta\left(\mathbf{r}-\mathbf{r}_p-\underline{\varepsilon}\left(t\right)\right)-\delta\left(\mathbf{r}-\mathbf{r}_p\right)\right] \tag{2}$$

where $\mathbf{r}_p$ is the equilibrium position of the rod, γ represents its strength (or Galanin's constant) and $\underline{\varepsilon}\left(t\right)$ characterizes its two-dimensional displacement from its equilibrium position. In the weak absorber formulation (i.e. when $\gamma \ll 1$), the induced neutron noise can be expressed as:

$$\delta\phi\left(\mathbf{r},\omega\right)=\gamma\underline{\varepsilon}\left(\omega\right)\cdot\nabla_{\mathbf{r}_p}\left[G\left(\mathbf{r},\mathbf{r}_p,\omega\right)\phi_0\left(\mathbf{r}\right)\right] \tag{3}$$

where $\phi_0\left(\mathbf{r}\right)$ is the static neutron flux without any rod present and $G\left(\mathbf{r},\mathbf{r}_p,\omega\right)$ is the Green's function. It should be noted that the differential operator on the right hand-side of Eq. (3) refers to the equilibrium position $\mathbf{r}_p$ of the rod. As typical in noise analysis problems, an inverse problem must be solved, i.e. one needs to determine from the neutron noise $\delta\phi\left(\mathbf{r},\omega\right)$ measured at a few discrete locations the position $\mathbf{r}_p$ of the vibrating rod. Due to the two-dimensionality of the problem, the unknown of the problems are the two components of the displacement vector $\underline{\varepsilon}\left(t\right)$ and the equilibrium position $\mathbf{r}_p$ of the rod. Access to at least three detectors is thus required to find the position $\mathbf{r}_p$ of the vibrating rod using a root finding (i.e. minimization) procedure.

The work performed by Imre first considered periodic perturbations using direct Fourier-transforms of the quantities before turning to stochastic perturbations using auto- and cross-power spectral densities of the quantities. The localization algorithm was based on the estimation of the Green's function of the system, considered to be fully homogeneous. It was then applied to measurement data coming from the Paks-2 PWR in Hungary performed in 1985. An excessively vibrating control rod could be successfully identified because of those investigations. The rod #4 in Fig. 2 was identified as the vibrating one. It is interesting to mention that a smaller vibration peak in the Auto-Power Spectral Density (APSD) of the detector #1 was measured, whereas this detector was the closest to the vibrating rod. This counter-intuitive behavior is explained by interference effects existing between the local component of the neutron noise and its point-kinetic component. The use of Artificial Neural Networks (ANNs) was also considered for unfolding the neutron noise source. This was accomplished by first training the ANN using Eq. (3). The only additional difficulty of this approach lies with the necessity to explicitly define a model for the vibrating control rod, i.e. the two-dimensional displacement vector $\underline{\varepsilon}\left(t\right)$ must be specified.

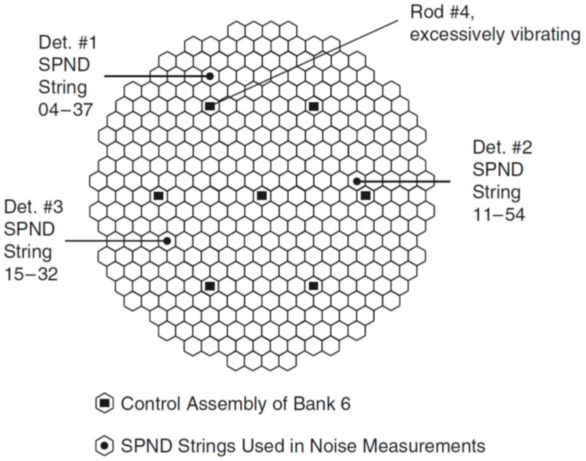


Fig. 2. Layout of the detectors used for the localization of an excessively vibrating control rod out of 7 possible ones in the Hungarian Paks-2 PWR in 1985 (from [5]).

2. Anomaly Characterization and Localization

More generally, some of Imre's work focused on anomaly characterization and localization. We can for instance refer to the detection of detector tube impacting in BWRs using both spectral techniques (see for instance [14, 15]) and wavelet-based techniques (see for instance [16]) with the interpretation of numerous measurement campaigns in BWRs in Sweden.

Neutron detector tubes in BWRs are located in the wide water gaps between fuel assemblies. Because of the turbulent character of the flow between those, the detector tubes might vibrate. Excessive vibrations might even lead to the detector tubes impacting with the fuel boxes surrounding the fuel assemblies. To avoid damaging the fuel boxes and ultimately the fuel cladding, it is important to detect vibrating detector tubes and possible impacting. This can be achieved by analyzing the signals of the Local Power Range Monitors (LPRMs) permanently installed in the detector tubes.

If one uses spectral methods, the detection of vibrating and possibly impacting tubes is based on a qualitative examination of the APSD of the LPRM signals and of the coherence and phase between LPRMs belonging to the same detector strings. In case of no vibration, a smooth structure of the APSD and coherence should be observed and no peak present. In addition, the phase should present a linear dependency corresponding to the transport timed of the vapor bubbles from the lowermost to the uppermost detector. In case of vibrations but without any impacting, a single and narrow peak appears in the APSD and coherence. In addition, the linear phase behavior that should be normally observed without vibrations is distorted, with a phase being typically equal to zero in the narrow frequency range of vibrations. In case of vibrations and impacting, a broad peak in the APSD is visible with the apparition of several peaks (essentially a peak at the double frequency of the fundamental mode). Again, the linear phase behavior is distorted and the phase is equal to zero on a large frequency range.

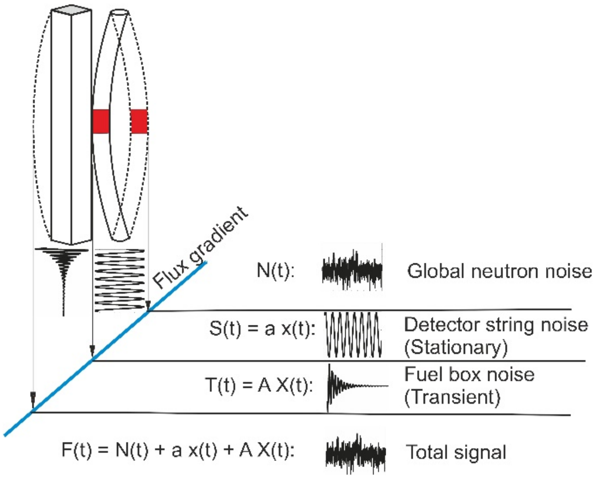
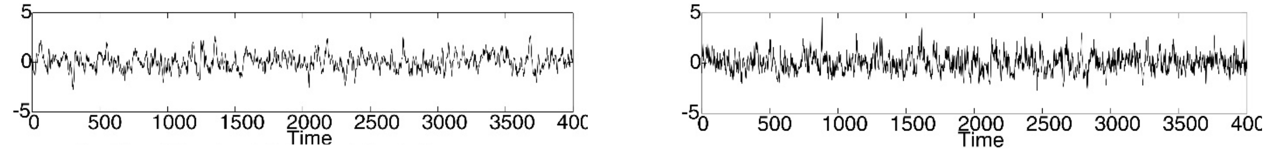


Fig. 3. Conceptual illustration of the different components of the neutron noise signal in case of vibrations and impacting (from [5]).

Spectral methods are more easily applicable if reference measurement data involving no vibration/impacting are available. The major drawback of such methods is that they rely on the necessary stationarity of the processes that one tries to detect. Intermittent processes, such as impacting, cannot be systematically detected. One way to deal with intermittences is to rely on wavelet-based methods. If a tube impacting with a fuel box induces a short and damped vibration of the assembly, the neutron noise induced by these short-lived vibrations or spikes should be visible in the neutron detector signal as well, as conceptually illustrated in Fig. 3. Using discrete wavelet transform and a thresholding of the wavelet transform coefficients before inverse transform (i.e. wavelet filtering), such intermittent spikes can be detected. The wavelet-based method was applied to neutron noise measurements performed at the Swedish Barsebäck-1 BWR in 1984. The results of the corresponding analysis are represented in Fig. 4, where it can easily be noticed that the LPRM 03.3 suffered heavy impacting, as compared with LPRM 18.3. The identification of impacting for LPRM 18.3 was confirmed by visual inspections during outage.



a) Detector signal LPRM 18.3

b) Detector signal LPRM 03.3

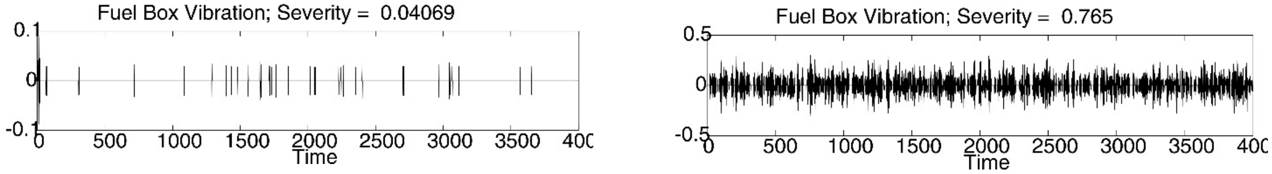


Fig. 4. Wavelet-based analysis of two LPRM signals: LPRM 18.3 (left) and LPRM 03.3 (right). The original signals are represented on the top figures, whereas the components of the signals related to fuel impacting are given on the bottom figures (from [16]).

3. BWR instabilities

Because of the Swedish fleet mostly constituted of BWRs, the diagnostics of BWR instabilities represented a special focus area in Imre's work, with the development of methods for detecting instabilities and classifying them (global, regional, and local oscillations) [18]. In case of global oscillations, the spatial dependence of the neutron noise follows the fundamental eigenmode of the system. Thus, any pair of neutron detectors located on the same axial plane should be in phase, i.e. the phase of their Cross-Power Spectral Density (CPSD) should be close to 0 deg. On the other hand, in case of regional oscillations, the spatial dependence of the neutron noise is a linear combination of the first two azimuthal modes of the system. The phase of any pair of detectors located on opposite sides from each other but on the same axial plane should be close to ±180 deg (i.e. out-of-phase from each other). A partial factorization method was proposed to extract the component of the neutron noise related to global oscillations, based on the property of orthogonality between the fluctuations of the shape function $\delta\psi\left(\mathbf{r},t\right)$ and the static flux $\phi_0\left(\mathbf{r}\right)$:

$$\int_V \phi_0\left(\mathbf{r}\right)\delta\psi\left(\mathbf{r},t\right)dV = 0 \tag{4}$$

thus leading to the factorization of the neutron noise as:

$$\delta\phi\left(\mathbf{r},t\right) = \frac{\int_V \delta\phi\left(\mathbf{r},t\right)\phi_0\left(\mathbf{r}\right)dV}{\int_V \phi_0^2\left(\mathbf{r}\right)dV}\phi_0\left(\mathbf{r}\right) + \delta\psi\left(\mathbf{r},t\right) \tag{5}$$

The first term on the right hand-side of Eq. (5) represents the point-kinetic term or global oscillation, whereas the second term represents what remains and which is a combination of several effects. Although it might be appealing to associate this term with the regional oscillations solely, it was showed that this term also contains the neutron noise induced by local perturbations, such as void fluctuations inevitably present in BWRs. Imre demonstrated, both theoretically and experimentally, that using the signals of detectors located on the same axial plane (thus the name of *partial* factorization) allows to minimize the local effect and to successfully extract the regional oscillations.

In addition to global and regional oscillations, BWRs can also experience local oscillations, typically driven by a Density Wave Oscillation (DWO). In addition to detecting such oscillations, one of the challenges is to be able to localize the driving perturbation [19]. Using detectors located on the same axial plane, a local oscillation can be regarded as a point-like source:

$$\delta\Sigma\left(\mathbf{r},\omega\right)=\gamma\left(\omega\right)\delta\left(\mathbf{r}-\mathbf{r}_0\right) \tag{6}$$

The induced neutron noise can thus be expressed as:

$$\delta\phi\left(\mathbf{r},\omega\right)=\gamma\left(\omega\right)G\left(\mathbf{r},\mathbf{r}_0,\omega\right)\phi_0\left(\mathbf{r}\right) \tag{7}$$

where $\phi_0\left(\mathbf{r}\right)$ is the static neutron flux and $G\left(\mathbf{r},\mathbf{r}_0,\omega\right)$ is the Green's function. $\mathbf{r}_0$ represents the location of the local oscillation (in a two-dimensional plane) and is the parameter that needs to be determined. Having access to several detectors, finding the location $\mathbf{r}_0$ of the noise source can be achieved by estimating the following function for every possible value of the variable $\mathbf{r}$:

$$\Delta\left(\mathbf{r}\right)=\sum_{A,B}\left[\frac{\delta\phi\left(\mathbf{r}_A,\omega\right)}{\delta\phi\left(\mathbf{r}_B,\omega\right)}-\frac{G\left(\mathbf{r}_A,\mathbf{r},\omega\right)}{G\left(\mathbf{r}_B,\mathbf{r},\omega\right)}\right]^2 \tag{8}$$

where the sum must be taken for each combination $\left(A,B\right)$ of the available detectors. The minimum of this function is obtained when the ratio of the measured neutron noise is the closest to the ratio of the calculated neutron noise, thus indicating a proper localization of the noise source (giving rise to the neutron noise pattern measured by the detectors). This should be achieved when $\mathbf{r}=\mathbf{r}_0$.

The method above was extended so that the APSD and CPSD of the measured signals could be used instead of their Fourier transform. The technique was thereafter applied to the Swedish Forsmark-2 BWR, where an unseated fuel assembly was discovered by visual inspection during the outage following the fuel cycle 16. An unseated fuel assembly results in a DWO and thus corresponds to a local oscillation in a two-dimensional representation of the reactor core. Such a DWO could thus be located using the algorithm presented above. Fig. 5 represents the results of the localization algorithm. It can be seen that the localization procedure was indeed able to pinpoint a region of the core close to the actual location of the actual unseated fuel assembly.

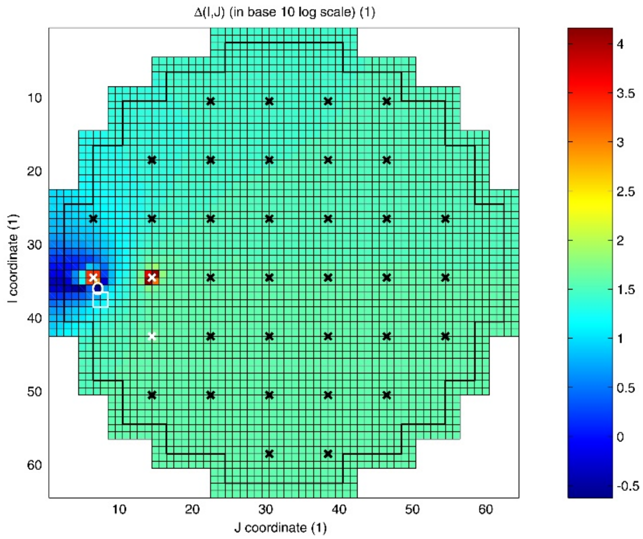


Fig. 5. Result of the localization algorithm in the Forsmark-1 case (local instability event). The unseated fuel element is marked with a square, and the noise source identified by the localization algorithm with a circle; the detectors that were used in the localization search are marked by white crosses, whereas the detectors that were not used are marked by black crosses (from [5]).

4. Core Barrel vibrations

More recently, the monitoring of core-barrel vibrations (beam- and shell-modes) retained Imre's attention [20, 21]. The focus on this area was triggered by an increase of the amplitude of the beam-mode oscillations in the Swedish PWRs at the Ringhals site and was the result of a long-standing yearly-based collaboration between Imre and the Ringhals nuclear power plant. This collaboration started in 1995 and is still on-going today. It encompasses both the analysis and interpretation of neutron noise measurements to detect possible changes and anomalies at the different units. When necessary, new models are developed and simulations performed accordingly to support the interpretation of measurements.

The core barrel in PWRs, which is a structure hanging vertically inside the reactor pressure vessel from its top, might vibrate during operation of the plant. Excessive vibrations might indicate some wear of some mechanical components in the vessel, especially at the radial support of the core barrel and core support plate. It is thus of prime interest to monitor and diagnose core barrel vibrations. Typically, two vibration modes are present, as illustrated in Fig. 6: the beam-mode (having an eigenfrequency of about 8 Hz) and the shell-mode (having an eigenfrequency of about 20 Hz). Because of the azimuthal equal spacing of the ex-core detectors around the core, the beam-mode can be extracted from the four detector signals $\delta\phi_k\left(t\right),k=1,\ldots,4$. The x

and y components of the beam-mode are proportional to a combination of the detector signals as:

$$\begin{cases} x(t) \propto \delta\phi_1(t) - \delta\phi_2(t) \\ y(t) \propto \delta\phi_3(t) - \delta\phi_4(t) \end{cases} \tag{9}$$

whereas the shell-mode vibrations are characterized by a displacement d proportional to the following combination of the detector signals:

$$d(t) \propto \delta\phi_1(t) + \delta\phi_2(t) - \delta\phi_3(t) - \delta\phi_4(t) \tag{10}$$

The separation of the beam- and shell-mode vibration spectra is illustrated in Fig. 7.

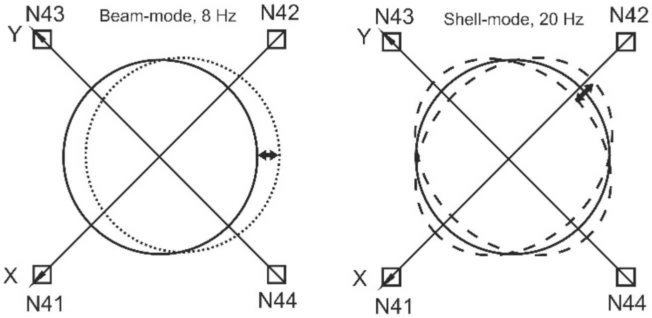


Fig. 6. Conceptual representation of the beam- and shell-mode vibrations of the core barrel in PWRs (the ex-core detectors are shown as squares and labelled N4X) (from [5]).

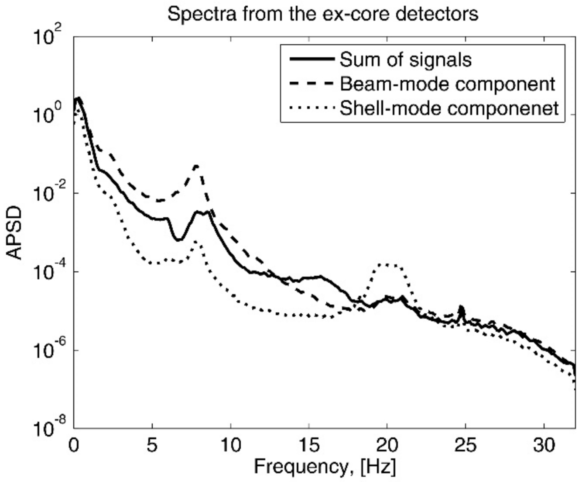


Fig. 7. Ex-core neutron detector spectra illustrating the different core barrel vibration modes. The measurement data were obtained at the Swedish Ringhals-3 PWR (from [5]).

A significant part of the research carried by Imre on core barrel vibrations aimed to understand a "periodic" behavior of the 8-Hz peak from cycle to cycle, with the amplitude of the peak increasing during a cycle and returning to a lower value at the beginning of the next cycle. Many studies combining the development of both analytical and numerical models and the analysis of plant data were conducted to understand this behavior. The fundamental question to be answered was whether the increase of the amplitude was indeed due to increased core barrel vibrations or to another physical process leading to an increase of the neutron noise. A recent investigation revealed that the 8-Hz peak is actually made of two components [22]: a contribution from the beam-mode vibration (at actually 7 Hz) overlapping with a contribution from fuel assembly vibrations (at 8 Hz). The former was demonstrated to remain constant during the cycle, whereas the latter was proven to increase.

5. Other projects

In addition to the collaboration with the Ringhals nuclear power plant, yearly projects between 1995 and 2012 were supported by the Swedish Radiation Safety Authority (formerly the Swedish Nuclear Power Inspectorate). These projects were aimed to establish long-term research on the development of diagnostics and monitoring methods for nuclear reactors.

The examples above represent a few of many areas of expertise that can be found in Imre's scientific portfolio. To name a few of Imre's other areas of interest, one could highlight the extension of the theory of power reactor noise to other types of reactors than light water reactors, most notably subcritical systems driven by an external source and molten salt reactors. One also needs to mention his extensive work on the theory of zero-power reactor noise and its application for safeguards and non-proliferation purposes. Imre, together with Dr. Lénárd Pál, wrote a book on this subject [23]. Imre has a very strong scientific record of accomplishment, with more than 200 peer-reviewed journal publications, covering all aspects of power reactor noise and zero-power reactor noise, as well as many other areas in neutron physics, transport theory, and reactor physics. In power reactor noise, the development of novel models combined with the analysis of actual plant data represents a unique feature of Imre's work.

IV. OUTLOOK AND CONCLUSIONS

As highlighted by Imre as well as by other noise analysis researchers, noise source unfolding was successfully demonstrated both with parametric and non-parametric inversion methods and both on simulated and measured signals. 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 reactor transfer function for non-homogeneous reactor cores with a high level of fidelity would make the methods viable for core diagnostics in power reactors on a routine basis. The estimation of a power reactor transfer function is nevertheless a far from trivial task, because of the numerous interwoven processes that take place in the core. These involve the transport and multiplication of neutrons throughout the system, the transfer of heat between the nuclear fuel elements and the cooling fluid, the transport of mass, momentum, and energy within the fluid, and possible fluid-structure interactions.

Past and current efforts in nuclear reactor core modelling usually rely on computer-based simulations, targeting either steady-state conditions or reactor transients. Even though the simulation platforms used for studying reactor transients are very mature, the modelling of stationary fluctuations remains a major challenge. As the transient tools were developed for modelling deterministic and large variations in reactor conditions, accurately catching the effect of stochastic and comparatively very small stationary fluctuations is difficult for such tools. Some of them make use of numerical diffusion for damping inherent numerical oscillations arising from ill-posed numerical schemes. An alternative better-suited approach is called for to solve this different class of problems. It relies on the development of numerical tools that shall be specifically designed for the modelling of such fluctuations and based upon the prior removal of the mean value from all fields. Such simulations can be performed in either the time-domain or the frequency-domain.

In neutron transport, Imre clearly identified early on the need of developing numerical tools for estimating the reactor transfer function, following the same principles as the ones used in the industrial static core simulators [24]. Several numerical tools have been developed since then. Nevertheless, at present the available modelling tools dedicated to the modelling of fluctuations are based upon very coarse methods with respect to spatial discretization, energy grid, and angular dependence of the neutron density field. They are therefore not immediately applicable to power reactors for investigating operational problems.

This might be the reason why despite the large amount of research performed and published, there are only very few cases where core monitoring relying on the inversion of the reactor transfer function determined for the actual heterogeneous configuration of the reactor is used on a routine basis in support to plant operation.

Chalmers University of Technology, with the present author as a coordinator, is leading a project to Euratom Horizon 2020 on core diagnostics based on neutron noise analysis. The project is called CORTEX and stands for CORe monitoring Techniques and EXperimental validation and verification. The project runs during the period 2017-2021 and includes 22 partners (including 3 non-European partners) from various horizons of the nuclear industry (academia, research institutes, technical safety/support organizations, utilities, servicing companies). The essence of CORTEX is to use noise analysis to early on detect anomalies in commercial nuclear reactors. The technique proposed in CORTEX is based on a non-parametric inversion of the reactor transfer function, that has to be estimated in advance with a high level of fidelity for strongly heterogeneous systems. The project thus comprises modelling activities targeted at estimating the reactor transfer function, with special emphasis on vibrations of reactor internals. Experimental programs in two research facilities will be specifically designed for validating the developed tools. It will be the first time ever such experiments are performed for the specific purpose of validating noise-specific modelling tools. The inversion of the reactor transfer function will rely on the latest advancements in machine learning techniques, after processing the detector recordings using advanced signal analysis methods. A large part of the project is devoted to the test and demonstration of the noise-based techniques using actual plant data coming from a large variety of reactor types and designs.

The CORTEX project, to which Imre contributed, is in accordance with many of the principles proposed and developed by Imre, and for which he has been striving. When completed, the project will demonstrate the usefulness and applicability of noise-based techniques to the nuclear industry.

ACKNOWLEDGMENTS

I am deeply thankful to Imre. Imre has been a driving force in nuclear engineering in Sweden at large and has shaped up research and education, having the highest international standards in mind. Because of the unfavorable political situation about nuclear energy in the country, the task was far from easy. Imre was always able to find new opportunities and take up the fight when necessary. I will always admire Imre for his positive thinking in harsh times and for his determination. Scientifically, Imre has been a mentor to me, with his endless knowledge in applied physics (reactor physics, reactor dynamics, neutron transport, etc.) but also in theoretical physics (stochastic processes, random processes, etc.). His recognition on the international scene clearly demonstrates the importance of his scientific contributions. On a more personal level, Imre has been working hard to establish a nuclear engineering “family” at Chalmers, including both the students and the staff members. Everyone knowing Imre could also testify about his mastery in telling anecdotes about past adventures in an entertaining manner. Caring about others, Imre is often referred to by his friends as a “true gentleman”. At many occasions, I could not help thinking about a Croatian cartoon from the 1960s and 1970s depicting a professor (professor Balthazar) who was always keen on helping others ;-)

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