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An Overview of the Collaboration in Diagnostics and Monitoring between Ringhals NPP and Chalmers University of Technology

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Abstract – *This paper describes some important aspects of a research collaboration between Ringhals NPP and Chalmers University of Technology, continuing for over 20 years. Important findings from reactor diagnostics and core monitoring using noise analysis methods are summarized, to show a broad perspective on the understanding of relevant problems as well as methods elaborated for their solutions.*

I. INTRODUCTION

A research collaboration in diagnostics and monitoring between Ringhals Nuclear Power plant (NPP) and Chalmers University of Technology, Sweden, was started and lead by Prof. Imre Pázsit in 1994, and has successfully continued in annual stages for over 20 years. The incentive for such collaboration began with the need to build up competence in reactor diagnostics at Chalmers, and has since developed into designated research areas. Especially neutron noise analysis methods have proven useful in characterizing certain properties of the operating nuclear reactor, which are hard to assess by other means. The driving force behind power uprates, and extended lifetime programs of nuclear power plants, highlight the need for elaborate methods for "fingerprinting" of the reactor characteristics, enabling trend following and elaborate tools for deeper investigations.

This paper gives an overview of the long-term research collaboration between Ringhals and Chalmers, with comments on the development of selected analysis methods, together with some important results and merits from an industrial point of view. The paper is concluded with some personal remarks.

II. NOISE ANALYSIS FOR REACTOR CORE DIAGNOSTICS

The initial phase of the collaboration between Ringhals AB and the former division of Reactor Physics (later renamed to division of Nuclear Engineering, and from 2015: division of Subatomic and Plasma Physics) at Chalmers University of Technology in Gothenburg, focused on tests by collecting different PWR-process signals with high resolution data acquisition equipment. Basic statistical properties of the data (ex-core neutron detectors, core exit thermocouples), for determining the quality and potential use of detector signals for further analysis, were systematically investigated [1].

The following stages in the collaboration [2-19] addressed several situations on how to make use of various combinations of detector signals (also including in-core detectors), for extracting useful properties of the reactor during operation. Development of some basic theoretical models made it possible to gain further insights in both the dynamical properties of the core, as well as trends in the mechanical behavior of reactor internals. The following sections give a brief overview of different problem areas where noise analysis from combinations of detector signals were useful for reactor diagnostics purposes at Ringhals 1 (BWR), and Ringhals 2-4 (PWR), together with some conclusions drawn from the analyses.

1. Core barrel vibrations in Ringhals 2-4

Vibrations of the core barrel is a source for wear of the lower radial support structure, and it is therefore of interest to monitor possible changes in vibration amplitudes with core burnup, and between different cycles. The pendular mode of the core barrel motion (CBM), and fuel assembly vibrations overlap in frequencies around 8 Hz, and separating the corresponding peaks in the auto power spectral density (APSD) from ex-core detector signals becomes important for trending any development of individual vibration amplitudes. The continuous work of improving the method for separating the different modes, in combination with neutron noise simulations, indicated that the spectral contribution from fuel assembly vibrations grows with burnup, while the corresponding CBM-peak does not show any significant trend. The question arises whether the increase in the spectral contribution from fuel assembly vibrations corresponds to the increase of the vibration amplitude itself, or to that of a burnup dependent scaling factor between the mechanical vibration effect and the ex-core neutron noise. Such calculations were performed, and show that if several fuel assemblies vibrate at various positions independently of each other, then the scaling factor shows a monotonic increase during the fuel cycle [20].

Recently, a new pivotal motion of the core barrel has been identified by properly combining all 8 ex-core detector signals in the analysis [19]. The vibration mode in question is a small amplitude periodic tilting movement of the core barrel around a horizontal, diagonal pivot at the half height of the core (crossing through the centre of mass of the core), referred to as the "tilting mode". The results indicate that also the upper support structure of the core barrel could be subject to wear, which is consistent with findings from the inspection program of the reactor internals. In Fig. 1, the results from enhancing the tilting mode component in the measured signals from Ringhals 4 in 2014, are shown as the evolution of the APSD within one cycle (from [19]).

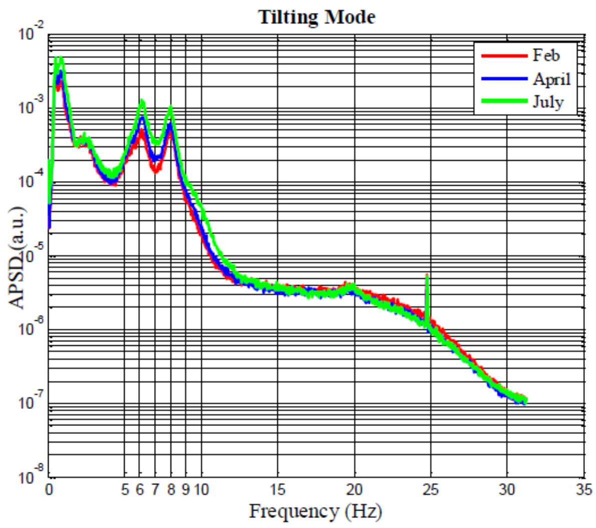

Fig. 1. Time evolution (within one cycle) of the APSD of combined ex-core signals, enhancing the tilting mode of core barrel vibrations, taken from [19].

2. Investigation of detector tube impacting in Ringhals 1

In connection to BWR stability measurements, local power range monitor (LPRM) vibrations can be identified by spectral analysis based on the features in the APSD, and phase and coherence between the detector signals in the same string. Broad peaks in the APSD around 2 Hz, and peaks at multiple frequencies (3-6 Hz,) are indications of impacting between the detector tube and the fuel channel [9, 10]. A discrete wavelet method was developed and tested together with a method based on the continuous wavelet transform [11]. Indications of impact from such methods offer guidance for directed inspection of high probability impact zones.

Following inspections have revealed, however, that wear at fuel channel corners from impacting detector tubes is not evident. Such a complete chain from initial measurements, through analyses by advanced wavelet filtering technique, to a directed inspection program, is a good example of a useful application.

3. Analysis of gamma-thermometer signals in Ringhals 2

For a period, the Ringhals-2 PWR was equipped with 12 strings of Gamma-Thermometers (GTs), each string containing 9 detectors located on different axial levels. The GTs are versatile instruments, and were to some extent part of an on-line system for monitoring thermal margins in Ringhals 2. A GT measures gamma heating proportional to local power and has a heating cable for in-situ calibration. The instrument might also be used to measure coolant flow as well as core coolant conditions. The collaboration with Chalmers included measurements of the coolant flow surrounding the gamma thermometers based on noise analysis. More specific, the GTs were used for mapping the radial distribution of the moderator temperature noise, for estimating the moderator temperature coefficient of reactivity, and for the determination of the axial distribution of the coolant axial flow velocity [6-9].

In 2003, Ringhals personnel noticed a degradation of the quality of the signals delivered by the GTs to the core monitoring system in the control room. Although the sampling frequency of the data acquisition system used by the core monitoring system is only about 10^{-2} to 10^{-3} Hz and is not high enough for noise analysis, it was easily noticed that some signals were extremely noisy and exhibited some sudden jumps. Since the signals recorded with the data acquisition system used for noise analysis exhibit the same features as the ones recorded by the plant monitoring system, it was claimed that the abnormal signals are due to the GTs themselves and not to the measuring chain [10]. However, the investigations came to an end when the gamma-thermometers were removed, as it became increasingly difficult to combine the fixed in-core detectors with the movable detector system.

4. Low frequency noise analysis in Ringhals 3 and 4

This study was motivated by a general increase in the neutron noise amplitude level, which has led to disturbances in certain alarms. By performing a cross-spectral and cross-correlation analysis of selected ex-core detector and core-exit thermocouple pairs, the radial dependence of the coolant velocity between the corresponding detector pairs can be studied, which could help to explain the origin of ultra-low frequency oscillations. The spectral analysis suggested that it was possible to obtain a reasonable estimation of the transit times by using a linear fit to the phase of the cross power spectral density (CPSD) function, indicating that there is a clear asymmetry in the radial flow distribution between different parts of the core.

An interesting feature was the presence of two different slopes in the phase of the coherence function observed for several detector pairs. Such a strange phase behavior had already been noticed in the early 70s, in the measurements performed for BWRs, but had never been confirmed for PWRs. The possible presence of two different slopes related to two different transit times in ex-core/ thermocouple measurements in a PWR can be explained by the convolution of two propagating perturbations travelling in opposite directions. In practice, the neutron detectors placed near the downcomer sense the same perturbation twice (downstreams in the downcomer, and upwards through the core), whereas the thermocouple can detect the perturbation only inside the core. Such a complex perturbation was modeled with two identical propagating perturbations travelling in opposite directions at some distance away from each other. The results of such a simulation from [18], for a two-dimensional case, is shown in Fig. 2. As seen in the figure, the presence of two signals in the simulation leads to the appearance two different slopes in the phase spectrum, with different corresponding transit times. One should, however, be aware of the fact that the neutron noise induced in the downcomer region can be considerably weaker than what is induced in the active part of the core, and could therefore be insignificant.

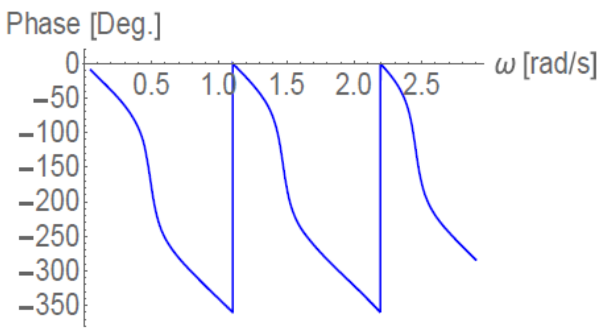

Fig. 2. Simulated phase of the CPSD from [18], calculated between a core exit thermocouple and an upper ex-core detector for the case of two perturbations propagating in opposite directions.

Another type of investigation implemented in 2012 and 2014, is a so-called multi-variable partial autoregression analysis, also known as Signal Transmission Path (STP) analysis. The main idea behind the STP is that for signals coupled through some physical process (feedback), it might be possible to point out which signal is the source, and which is the affected one by analyzing the measured fluctuations in the respective signals. Such a method provides both the information about different coupling mechanisms between measured signals, as well as the main source driving the phenomenon.

From the STP-analysis, some correlations between ex-core neutron detector and core exit thermocouple measurements were found, which lead to the conclusion that for ultra-low frequencies (f < 0.1 Hz), the neutron noise is most likely driven by the temperature fluctuations. However, this is not the case for the low frequency region (f > 0.1 Hz), where the situation becomes reverse, *i.e.* the fluctuations in thermocouple signals are apparently caused by the fluctuations in corresponding neutron detector signals, which in turn are induced by some other external sources. An example of the noise power contribution (NPC) from [18], between an ex-core detector and two core exit thermocouples, demonstrating the different behavior in the low and ultra-low frequency regime, can be seen in Fig. 3.

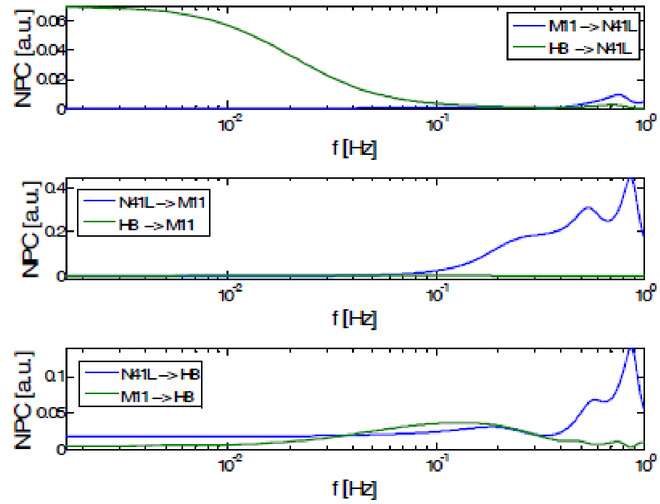

Fig. 3. The noise power contribution between ex-core detector N41L, and two core exit thermocouples (M11, H8), taken from [18], demonstrating two different regimes at low, and ultra-low frequencies.

III. RESULTS AND MERIT

The results from the collaboration between Ringhals and Chalmers are documented in annual research reports [2-19], and have resulted in a number of journal- and conference papers (references within the annual reports).

During the years, the projects have involved technicians, master-thesis students, PhD-students, post docs, and senior researchers at Chalmers, as well as engineers and physicists from Ringhals NPP. The benefits from such a close collaboration are best seen in the opportunities to address the actual and potential problem areas identified during operation of NPPs, and from inspections during outages, which regularly constitute the base for annual research project proposals.

Research relevant for the industry usually attracts the interest from students choosing their master thesis projects, and has shown to be an attractive entrance to the nuclear industry. The more advanced projects are often suitable for involving PhD-students, whom also have the possibility to perform some of the studies on-site, especially in designated industrial PhD-projects. The collaboration between Ringhals and Chalmers have resulted in many such successful examples, and a number of master- and doctoral theses have been produced in connection to this collaboration. Several of these students have also been awarded the Sigvard Eklund's prize for best theses, which demonstrate the significance of their work, and serve as good examples of education and research going hand-in-hand.

IV. PERSONAL REMARKS

In order to further address the importance of the collaboration between Ringhals NPP and Chalmers University of Technology, some personal remarks from the authors follow below.

1. Personal remarks from the first author

I became actively involved in the Ringhals and Chalmers research collaboration around 2005, and further engaged in 2011, when I had the opportunity to join the division of nuclear engineering at Chalmers as adjunct professor. Such an arrangement deepens many aspects of a collaboration, especially when identifying relevant problem areas for the nuclear industry, suitable for approaching in an international research environment. I would like to express my true pleasure of working with Imre, having the opportunity for continuous learning while enjoying entertaining stories from the academic world.

2, Personal remarks from the second author

Imre was my advisor and examiner for my licentiate work at Chalmers. He helped me to merge my academic interest with my position as an engineer at the Ringhals plant. I found core diagnostics the perfect merger of science and engineering. In addition to the basic functions of the nuclear instrumentation, core diagnostics made it possible to look further into the core, extract more information and to detect changes as they occur. From reading Imre's papers/reports, I came to realize the importance of presenting scientific results in an elegant, precise and condensed way. I also found the cosmopolitan environment of his department very stimulating.

NOMENCLATURE

APSD = Auto Power Spectral Density
BWR= Boiling Water Reactor
CBM = Core Barrel Motion
CPSD = Cross Power Spectral Density
GT=Gamma Thermometer
LPRM = Local Power Range Monitor
NPC=Noise Power Contribution
NPP = Nuclear Power Plant
PWR= Pressurized Water Reactor
STP = Signal Transmission Path

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www.nephy.chalmers.se/research/Ringhals/projects.html.

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