A STOCHASTIC METHOD FOR NUCLEAR POWER PLANT DIAGNOSIS

R. B. Perez* and R. T. Wood*

The University of Tennessee
Knoxville, Tennessee 37916

INTRODUCTION

The value of using neutron noise descriptors, especially the power spectral densities (PSDs) of ex-core detectors, to monitor core barrel motion and fuel element vibrations in pressurized water reactors (PWRs) is well established.¹⁻⁶ Indeed, in the mid-frequency range (1-20 Hz), PWR neutron noise is dominated by vibration peaks in the neutron PSD that result from the motion of reactor internals. A qualitative examination of such descriptors from a 1150 MWE Westinghouse PWR plant, revealed significant changes in the plant's noise signature (PSD) as its first fuel cycle proceeded. The purpose of this work is to use a mathematical model of the interaction between small mechanical motions and the core neutronics to provide a tool for quantitative investigation of the PSD structure in the vibrational frequency range.⁷

The purpose of neutron noise analysis is to provide information on plant conditions by the study of power traces from ex-core detectors. Due to the action of the coolant flow through the core and pump induced vibrations, the core barrel, which is bolted at the top of the reactor vessel, performs a pendular motion with a natural frequency determined by the mechanical parameters and constraints of the system.²⁻⁵ In addition, external forces deform the cylindrical shape of the core barrel by inducing vibrational modes which are excited by the turbulence of the coolant flow and by the "table-shaker" effect of the core barrel motion. As a result of the various mechanical motions, the detector response will vary in a manner proportional to the importance function at the location of the disturbance.

A typical ex-core neutron detector normalized PSD for a 1150 MWE PWR is shown in Fig. 1. Below 1 Hz the PSD is dominated by the feedback thermal hydraulic loop effects which evolve with time constants of the order of seconds. Between 3 Hz and 30 Hz, the PSD exhibits a set of resonances arising from the vibrational and pendular modes previously discussed. This disparity in the "natural" frequencies of the system is a fortunate break for the noise analyst as one can perform the modeling of the feedback and mechanical effects in a separate fashion.

IDENTIFICATION OF PSD STRUCTURE

It can be shown⁷ on the basis of first order perturbation theory that the neutron detector PSD, $\phi_{11}(\omega)$, is given by the expression:

$$\phi_{11}(\omega) = \sum_{\lambda} \left\{ \frac{\mu_{\lambda} A_{\lambda} + (\omega - \nu_{\lambda}) B_{\lambda}}{\mu_{\lambda}^2 + (\omega - \nu_{\lambda})^2} + \frac{\mu_{\lambda} A_{\lambda} - (\omega + \nu_{\lambda}) B_{\lambda}}{\mu_{\lambda}^2 + (\omega + \nu_{\lambda})^2} \right\}, \quad (1)$$

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831.

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

where the subindex λ varies over the frequencies of the mechanical vibrations and where we introduce the pole strength and asymmetry factors, A_λ and B_λ , respectively. The result in Eq. (1) shows that the neutron detector PSD is the superposition of a set of resonances at the various frequencies ν_λ . The line shapes are asymmetric with respect to the resonance peak because the term $(\omega - \nu_\lambda)$ changes sign as it goes through the resonance maximum. The second term within the bracket in Eq. (1) is a nonresonant term arising from the reflection of complex poles at negative frequencies.

The parametric model in Eq. (1) has been implemented in the program "CARDIOGRAMA" which performs a least squares fit of the functional relation to measured neutron PSD data. A typical result of the Cardiograma algorithm is shown in Fig. 2, where the data points correspond to the PSD of one of the ex-core neutron detectors at the 1150 MWE PWR SEQUOYAH-1 nuclear power plant. The resonance at 6 Hz has been associated with the pendular motion of the core support barrel (CSB). The peaks at 3.6, 8 and 16 Hz correspond to fuel element vibrations. Two shell mode resonances have been identified: a core barrel shell mode at 12 Hz and a pump-induced shell mode at 20 Hz. The evolution of the neutron PSD as a function of time and power level has been followed for nearly two full cycles at the SEQUOYAH-1 plant.⁵ A short-term and several long-term effects have been observed.

The short-term effect observed consisted of the shifting of the fuel vibrational peaks towards lower energies following a decrease in power, while the core barrel and shell model resonance frequencies remain unaltered. Among the various long-term effects, PSDs and CPSDs of the neutron noise exhibit a resonance at frequency of approximately 6.7 Hz. Phases between the cross-core detectors at this frequency are always 180° and the coherence is always greater than 0.8, thereby indicating pendular CSB motion. Another resonance at 8.0 Hz, having the same coherence and phase relationships can also be resolved in the PSDs and CSPDs at the beginning of the first fuel cycle. This resonance occurs at approximately the second mode of fuel assembly vibration (the first mode occurs at 3.6 Hz) as deduced from in-core neutron noise measurements made at SEQUOYAH-1. The fuel assembly fundamental mode decreased in frequency over the first fuel cycle to 3.0 Hz with a corresponding decrease in the second mode resonant frequency. This second mode resonance merged with the CSB resonance (6.7 Hz) to form what appears to be a single broad peak in the 5 to 7.5 Hz range, as shown in Fig. 3. The normalized root mean square (NRMS) of the neutron noise (at nominal full power conditions) in the 5- to 10-Hz frequency range increased by a factor of five from the beginning to the end of the first fuel cycle. At the beginning of the second fuel cycle, the neutron noise amplitude in this same frequency range decreased, but only to a level somewhat higher than at the beginning of the first cycle and resonances could be distinguished only at 3.0 and 7.0 Hz.

RESULTS

In this section, we discuss the application of the present stochastic model to the interpretation of the neutron PSD in the vibrational region. Of the observed long-term effects the most worrisome one is the "disappearance" of the core barrel resonance at the end of the first cycle.

To answer this question, measured PSDs from SEQUOYAH-1 taken at various times during the first and second fuel cycles were fitted using the stochastic model that was developed. Table 1 lists the frequencies and pole-strength factors for the first two fuel element resonances and for the core barrel peak. These results, which were obtained from plant signatures at the beginning, middle, and the end of the first fuel cycle and at the middle of the second fuel cycle, reveal the following features:

- (a) the pole strength factors for the first and second fuel resonances increased considerably between April '82 and August '82;

- (b) the fuel element peaks shifted towards the low frequency end of the spectrum; and
- (c) the pole-strength factor for the core barrel peak remained fairly constant since April '82, at a level of about one order of magnitude with respect to the value found in April '81.

The large increase in the pole-strength factor and the frequency shift of the second fuel element vibrational mode account for the disappearing act performed by the core barrel peak. However, the ability of the stochastic model to describe the structure of the neutron PSD and to separate the various mechanical motions allowed confirmation that the core barrel motion had not changed. This feature of the model is illustrated in Fig. 4. It can be seen that the broad peak around 7 Hz was interpreted as the contributions arising from the core barrel peak and the second fuel mode vibration. Note that the fitting program would have failed to work properly without the information gathered from earlier data throughout the fuel cycle, where the core barrel resonance was not masked by the resonance at 8 Hz. In fact, the "CARDIOGRAMA" program refused to fit that broad peak with only one resonance. The use of a core barrel contribution, with parameter guesses based on previous experience, was needed to achieve the functional fit shown in Fig. 4.

Examination of Table 1 reveals two plant "aging" effects: (i) the increase of the pole strength function between April '81 and April '82 for the core barrel peak indicates some "loosening" of the core barrel restrictions, and (ii) the shift of the fuel element resonances towards lower frequencies shows a decrease in the "stiffness" of the core's mechanical configuration.

CONCLUSIONS

In summary, first order perturbation theory has been used to relate the response of a neutron detector to small mechanical motions of the reactor internals. By mathematically manipulating the model, an equation for the neutron PSD was obtained that describes each motion in terms of a pole-strength factor, a resonance skewness factor, a vibration damping factor, and a frequency of vibration. This formulation allows each resonance peak to be quantified in terms of four identifiable parameters. The model was fitted to measured PSDs obtained from a PWR at various times during a fuel cycle. The mechanical motion parameters for several resonances were tracked to determine trends that indicated changes in vibrations within the reactor core. In addition, the resonance model gave the ability to separate the resonant components of the PSD after the parameters have been identified. As a result, the behavior of several vibration peaks were monitored over two fuel cycles.

REFERENCES

1. J. A. Thie, *Power Reactor Noise*, (LaGrange, IL, American Nuclear Society, 1981).
2. D. N. Fry et al., "Use of Neutron Noise to Detect BWR-4 In-Core Instrument Tube Vibrations and Impacting," *Nucl. Technol.* 43 (1979).
3. W. Bastl, R. Sunder, D. Wach, "On-Line Vibration Monitoring of PWR Internals," *Proceedings of ANS/ENS Topical Meeting on Thermal Reactor Safety* (1980).
4. R. Sunder, D. Wach, "Reactor Diagnosis Using Vibration and Noise Analysis in PWRs," presented at the International Symposium on Operational Safety of Nuclear Power Plants, Marseilles, France, 1983.

5. F. J. Sweeney, J. March-Leuba, C. M. Smith, "Contribution of Fuel Vibrations to Ex-Core Neutron Noise During the First and Second Fuel Cycles of the Sequoyah-1 Pressurized Water Reactor," *Prog. in Nucl. Energy* **15** (1985).
6. F. J. Sweeney, J. P. Renier, "Sensitivity of Detecting In-Core Vibrations and Boiling in Pressurized Water Reactors Using Ex-Core Neutron Detectors," ORNL/TM-8549, Oak Ridge National Laboratory (1985).
7. J. March-Leuba, G. de Saussure, and R. B. Perez *Trans. Am. Nucl. Soc.* **44** (1983).

Acknowledgement

Research sponsored by Office of Nuclear Physics, U.S. Department of Energy under contract number DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-84OR21400. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

Table 1. Vibrational Frequencies, ν_λ (Hz), and Normalized Pole Strength Factors, A_λ (dimensionless), at Selected Times During the First and Second Fuel Cycles

Date Recorded	Frequency (Hz)			Pole Strength Dimensionless		
	F1 ^a	CB ^b	F2 ^c	F1	CB	F2
April 81 ^d	3.55	7.03	7.82	$4.78 \cdot 10^{-8}$	$8.07 \cdot 10^{-8}$	$9.22 \cdot 10^{-8}$
April 82 ^d	3.34	5.88	7.46	$6.91 \cdot 10^{-8}$	$4.31 \cdot 10^{-7}$	$4.48 \cdot 10^{-7}$
Aug. 82 ^d	3.08	5.68	7.25	$1.04 \cdot 10^{-7}$	$3.25 \cdot 10^{-7}$	$1.38 \cdot 10^{-6}$
Aug. 83 ^e	3.07	5.97	7.26	$2.53 \cdot 10^{-7}$	$2.80 \cdot 10^{-7}$	$1.39 \cdot 10^{-6}$

^aFuel element first vibrational mode.

^bCore support barrel.

^cFuel element second vibrational mode.

^dFirst fuel cycle.

^eSecond fuel cycle.

Figure 1. Power spectral density for an ex-core neutron detector at a typical Westinghouse PWR. The data are normalized to the steady state power level.

Figure 2. Ex-core neutron detector power spectral density from the Sequoyah-1 Nuclear Power Plant. The points correspond to measured data. The continuous curve is the result of a Cardiograma fit.

Figure 3. Typical ex-core neutron detector power spectral densities through the first and second fuel cycles at the Sequoyah-1 Nuclear Power Plant.

Figure 4. Cardiograma fit to the ex-core power spectral density showing the contributions from the first and second fuel vibrational modes and from the core support barrel pendular motion.