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ADVANCES IN AUTOMATED NOISE DATA ACQUISITION AND NOISE SOURCE MODELING FOR POWER REACTORS

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ABSTRACT

A newly-expanded program, directed toward achieving a better appreciation of both the strengths and limitations of on-line, noise-based, long-term surveillance programs for nuclear reactors, is described. Initial results in the complementary experimental (acquisition and automated screening of noise signatures) and theoretical (stochastic modeling of likely noise sources) areas of investigation are given.

KEYWORDS

Noise analysis; stochastic modeling; reactor surveillance; feature recognition; Langevin conjecture; detector adjoint; fuel assembly vibration.

INTRODUCTION

A newly-expanded program, directed toward achieving a better appreciation of both the strengths and limitations of on-line, noise based, long-term surveillance programs for nuclear reactors, is in progress at the Oak Ridge National Laboratory (ORNL). The program comprises complementary experimental (data acquisition and screening) and theoretical (stochastic modeling) efforts, as described below. Our principal objective is to obtain a better understanding of reactor behavior in the long term by monitoring the constancy of known phenomena (such as fuel element and control rod vibrations, core support barrel motion, etc.) over a range of plant operating conditions (such as temperature, power level, boron concentration, accumulated operating time, etc.).

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AUTOMATED NOISE DATA ACQUISITION

The idea that an on-line, continuously operating, noise-based surveillance system might be useful in improving both the safety and availability of commercial power reactors has been pursued and developed by ORNL researchers for a number of years and has now reached the stage of initial demonstration of a prototypic system at Sequoyah Nuclear Plant, an 1148 MWe four-loop Westinghouse PWR operated by the Tennessee Valley Authority (TVA) and located near Chattanooga, Tennessee.

Software

Since the system's primary function is to amass a complete and relatively long-term data base of high-quality documented noise signatures, an important system feature is its ability to screen the incoming data and thereby to identify and record for subsequent scrutiny by a noise analyst only those signatures which depart, in a statistically significant manner, from the data patterns which the system has previously established as "normal" for a given set of plant operating conditions. This screening function is performed using a number of statistical descriptors derived from the power spectra of the plant signals being monitored, as reported by Piety (1977) at SMORN-II.

Hardware

The digital portion of the hardware consists of a PDP-11/34 minicomputer communicating with 96k words of random-access memory and 3.75 M words of disk storage. The analog portion comprises filter/amplifier modules of ORNL design having computer-selectable gains and cutoff frequencies, so as to accommodate both signals used for noise analysis and those used for "labeling" purposes (i.e., documentation of plant operating conditions prevailing at the time of the noise measurements). To avoid time skew, sample/hold circuits are provided for each input channel, and the conversion rate of the single 12-bit analog-to-digital converter is adjustable (by computer command) so as to provide the various analysis bandwidths desired.

As a temporary measure to meet Sequoyah's spring 1981 startup schedule, we initially installed sufficient analog hardware to process only four noise signal inputs simultaneously: three lower-core neutron power-range chambers and one pressure indication from coolant loop No. 4. In addition, 15 signals were used as labels, along with hour and date, for correlating signature changes with altered plant conditions. However, this temporary system has since been replaced (late August 1981) with an expanded version having sixteen inputs that are available for both noise analysis and labeling.

Interfacing and Remote Access

Though only temporary in nature, installation of the surveillance system at Sequoyah necessitated close coordination among ORNL and TVA personnel to ensure that neither noise signal fidelity nor plant safety was compromised in interfacing the signal processing hardware with the 23 plant signals made available for study (seven are ex-core neutron signals; the balance are coolant system flow, pressure, temperature, vibration, and level indications). These requirements were met by the installation of a special signal patch panel and low-drift, differential, transformer-coupled isolation amplifiers, which effectively buffered the surveillance system inputs from large-amplitude noise spikes that were found to be introduced on some sensor lines by operation of the plant's standard data logging computer.

Since Sequoyah is remote from ORNL (both in terms of its 160 km distance and its limited access to non-TVA personnel), a dedicated telephone line was installed to link the on-line surveillance system with a data/control terminal located at ORNL. This remote access arrangement permits noise analysts to verify surveillance system performance, to alter system parameters (e.g., data sampling rate and length of the "learning" period), and to plot spectral data without the necessity of leaving the laboratory. These capabilities have proved extremely useful in the initial phase of the project and we highly recommend the approach to others who may be contemplating the installation of an unsupervised system.

Experience to Date

The noise data acquisition system has now been connected to Sequoyah for ~7 months, during which time both the plant and the system have been undergoing checkout and correction of the

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Experience to Date

The noise data acquisition system has now been connected to Sequoyah for ~7 months, during which time both the plant and the system have been undergoing checkout and correction of the inevitable problems associated with new equipment. Nonetheless, a good set of spectral data have been acquired over a variety of operating conditions; a representative sampling is shown in Figs. 1-4.

Low-frequency (0.03-1.0 Hz) neutron and primary system pressure noise spectra are plotted in Fig. 1 for three different reactor power levels. Thirty-six individual spectra are overlaid for comparison. The broad resonance in the pressure spectrum at ~0.6 Hz appears to be related to primary system hydraulics (corresponding oscillations in pressurizer liquid level have been observed), and is independent of reactor power. In contrast, the pressure signal resonance at ~0.1 Hz is definitely affected, both in amplitude and frequency, by reactor power. Although only conjecture at the present stage of our study, this resonance is thought to be related to changing conditions on the secondary side of the steam generator. Except for a general decrease in variability with increased reactor power, the neutron spectra exhibit no noteworthy features in this low-frequency range of analysis. The overall amplitudes of the spectra vary as the square of the reactor power.

Figure 2 shows the spectra of the same two plant signals in the mid-frequency (0.3-10 Hz) range; the reactor condition was ~95% full power. The neutron spectra (upper curves) display the typical features widely described in the literature, namely, evidence of fuel assembly vibrations (3-5 Hz) and core barrel/reactor vessel vibrations (6-9 Hz). The pressure spectrum

Fig. 1. Low-frequency pressure and neutron flux spectra, February 1981.

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Fig. 2. Mid-frequency pressure and neutron flux spectra, April 1981.

Fig. 3. Variation of the coolant loop No. 4 pressure signal over a two-month interval.

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Fig. 4. Variation of the neutron flux spectrum over a two-month interval.

(lower curve) displays the 0.6 Hz resonance noted previously and a second resonance at ~ 4.5 Hz. This latter feature is of particular interest because its frequency has been observed to vary erratically (over a range of about 4-13 Hz) and sometimes disappears altogether (Fig. 3). Although we have not yet identified the source of these higher-frequency pressure fluctuations, their constancy points to a need for long surveillance periods to determine their underlying cause and to define a statistically meaningful baseline for normal plant operation.

Variations in the neutron noise spectra over a two-month time period are shown in Fig. 4 for a still broader range of frequencies (1-40 Hz). One interesting observation is that, with the passage of time, the resonant features appear to be becoming somewhat better defined, and possibly narrower. This may be indicative of the plant's "relaxing" into its ultimate, natural modes of movement and vibration as impediments to free motion are gradually removed by wear. Surveillance over an extended period will be required to clarify this observation, made early in plant life.

NOISE SOURCE MODELING

In anticipation of a need relative to the Sequoyah noise data acquisition project, one- and two-dimensional space- and energy-dependent neutron kinetics calculations were performed in the frequency domain to determine the response functions of ex-core neutron detectors to various postulated noise sources within the reactor core. In particular, since vibrations of PWR fuel assemblies have been observed (Wach and Sunder, 1977; Mayo and Currie, 1977) through their influence on the noise signals received by ex-core neutron detectors, there was interest in quantifying the amplitude of these vibrations. To do so, the spatial sensitivity function of the detectors, as well as the neutron flux perturbation resulting from the mechanical vibrations, must be known.

We determined the spatial sensitivity of an ex-core detector to lateral vibrations of fuel assemblies using the space-, energy-, and frequency-dependent neutron kinetics code TASK (Buhl and colleagues, 1972) and the Langevin source conjecture. As described in greater detail in subsequent sections, TASK was utilized to determine the spatial sensitivity to neutron sources (the detector adjoint), and the Langevin source conjecture was used to treat the vibrations as fluctuating neutron sources generated by the static neutron flux acting on fluctuating cross sections.

Previous Work

Previous studies of the ex-core neutron detector response to perturbations inside a reactor core have been based on fixed-source shielding calculations (Crump and Lee, 1978; Assedo and colleagues, 1979) or point kinetics (Thie, 1975; Saxe and colleagues, 1980). Since external neutron sources are not defined in a critical reactor (the addition of sources to a critical core results in supercriticality) a fixed-source shielding analysis models the perturbation (such as fuel assembly vibrations) as a fixed source of neutrons and the core as a purely attenuating medium (i.e., no fission is allowed). Such analysis neglects the propagation of

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Methodology

To overcome the inherent disadvantages of these two approaches and to study the ex-core detector response to fuel assembly lateral vibrations, we utilized the Langevin source conjecture, coupled with reactor kinetics codes, as stated earlier. In this manner the space dependence of the ex-core detector sensitivity is accounted for and, because the reactor transfer function becomes finite as the delayed neutrons decay (for frequencies not equal to zero), propagation of perturbations through fission processes can be treated.

In the Langevin source conjecture, the vibrating fuel assembly is modeled as a fluctuating source.

$$\delta S = \delta \Sigma \bar{\phi} \quad (1)$$

where $\delta \Sigma$ is a fluctuating space- and energy-dependent macroscopic cross section and $\bar{\phi}$ is the static flux at the perturbation location in the core.

A fluctuating flux at the ex-core detector location resulting from the Langevin source is calculated using the forward space-, energy-, and frequency-dependent Boltzmann equation. In operator notation,

$$L \delta \phi = \delta S \quad (2)$$

where L is the forward space-, energy-, and frequency-dependent Boltzmann operator.

For a few detector locations and spatially distributed noise sources it is more convenient to use the equivalent adjoint formulation:

$$\langle \Sigma_d \delta \phi \rangle_{v_d} = \langle \phi^\dagger \delta S \rangle_{v_p} \quad (3)$$

where

$$L^\dagger \phi^\dagger = -\Sigma_d \quad (4)$$

and

$L^\dagger$ is the space-, frequency-, and energy-dependent adjoint Boltzmann operator;

$\phi^\dagger$ is the detector adjoint;

Σ_d is the detector macroscopic cross section; and

$\langle \rangle$ indicates phase space integration over detector volume (d) or perturbation volume (p).

Again, Eqs. (3) and (4) are formulated as space-, energy-, and frequency-dependent problems. Equation (3) is a linearized formulation of the detector response and is equivalent to first-order perturbation theory; we justify its use on the basis that only small-amplitude fuel assembly vibrations about a mean location will be considered.

Detector Adjoint Calculations

We calculated the space-, energy-, and frequency-dependent detector adjoint in Eqs. (3) and (4) using both the one-dimensional transport kinetics code TASK (Buhl and colleagues, 1972) and the two-dimensional diffusion kinetics code JPRKINETICS (Renier, 1976). The 1-D calculations were performed with P_3 scattering, S_4 angular quadrature, and three neutron energy groups. The ex-core detector was assumed to be sensitive only to neutrons in the thermal group. The core was modeled as a 1-D radial slice through its center, as shown in Fig. 5. The enrichment pattern

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The following cases were studied:

- (a) $k = 1$, boron concentration 2100 ppm
- (b) $k = 0.995$ (altered transverse leakage)
- (c) $k = 1$, boron concentration 2150 ppm
- (d) $k = 1$, boron concentration 2100 ppm, with pressure vessel and shield.

In Fig. 6 the thermal neutron energy detector adjoints are shown for cases (a) and (b) above. The magnitudes of the detector adjoint in the core are seen to be sensitive to the assumed state of the reactor. Unlike the results from static shielding calculations, the calculated detector adjoints shown in Fig. 6 differ by less than one order of magnitude from the core edge to the core center. Moreover, the adjoints are quite space-dependent, thereby indicating that

FUEL ELEMENT

U-235 ENRICHMENT (W%)

1	3.18
2	3.18
3	2.0
4	2.55
5	2.0
6	2.55
7	2.0
8	2.55

Fig. 5. One-dimensional slab geometry of Sequoyah PWR core.

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Fig. 6. Thermal-group detector adjoints at 3 Hz, for $k=1.0$ and $k=.995$ [cases (a) and (b)].

Fig. 7. Thermal-group detector adjoints at 3 Hz, with and without pressure vessel [cases (a) and (d)].

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Fig. 8. Thermal-group detector adjoint at 3 Hz, for two-dimensional X-Y (radial plane) model.

point kinetics are not applicable to large light-water reactor (LWR) cores, at least at a frequency of 3 Hz.

The sensitivity of these results to small changes in boron concentration was studied by increasing the concentration to 2150 ppm and then readjusting the transverse leakage so that the core was again exactly critical [case (c)]. The results are practically indistinguishable from case (a), indicating that the calculated detector adjoints are not sensitive to small changes in the boron concentration. We are presently studying the effects of the somewhat larger changes that are associated with fuel burnup and changes in the core composition. We have not studied the effects of control rod positions.

To study the effect of the steel reactor pressure vessel and concrete biological shield on the detector response, the core was modeled as shown in Fig. 5 with 30 cm of water replaced by 10 cm of concrete and 20 cm of steel. The air gap between the pressure vessel and the biological shield was treated as a vacuum, and the detector was assumed to be positioned at this interface. Figure 7 compares the thermal-group detector adjoints computed for the two geometric modelings, cases (a) and (d). As expected, the relative attenuation across the core does not change appreciably; however, the absolute magnitudes of the adjoints are different. This result indicates that inclusion of different ex-core materials will probably not markedly affect the relative sensitivity with which fuel assembly vibrations can be detected at different core locations, but the absolute magnitudes predicted by these calculations will be heavily influenced.

We also performed two-dimensional, diffusion theory, space-, frequency-, and energy-dependent calculations. While our studies are incomplete at this writing, the actual magnitudes of both the detector adjoints and the attenuations across the core appear to be smaller for the 2-D than for the 1-D calculations. Figure 8 shows an X-Y plane (radial), 1/4 core, plot of the thermal group detector adjoint.

In connection with the preceding, it should be emphasized that the behavior of the detector adjoint alone does not provide a direct measure of the spatial sensitivity of an ex-core detector to a particular perturbation, since the detector response is the result of an integration of the product of the Langevin source and the detector adjoint in an appropriate phase space. The Langevin source is determined by the type of perturbation and the physical processes that occur as a result of the perturbation. Therefore, it would not be reasonable to expect the spatial sensitivity of an ex-core detector to be the same for different perturbations (e.g., fuel assembly vibrations vs. moderator boiling).

Formulation of the Langevin Source and Calculation of the Ex-Core Detector Response To Fuel Assembly Vibrations

Equation (1) shows the general formulation of the Langevin source as a fluctuating cross section. Since the ex-core detector response will depend upon the random amplitudes and orientations of the fuel assembly vibrations relative to both the detector and other fuel assemblies, the equations of motion for a fuel assembly were developed in terms of a probability density. The variance of the amplitude and direction of a single fuel assembly with random amplitude and direction and zero mean displacement is given by

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$$E \{ X^2(z) \} = \int_0^{2\pi} \int_{-\infty}^{+\infty} X^2(\Delta R, \theta, z) P(\Delta R, \theta, z) dR d\theta \quad (5)$$

where θ = displacement direction measured from an arbitrary point;

ΔR = displacement of fuel assembly from its mean position; and

$P(\Delta R, \theta, z)$ = joint probability density of amplitude and direction as a function of axial position, z

E = expected value operator.

The fuel assembly displacement and direction were assumed to be independent and the displacement amplitudes Gaussian distributed. The probability density¹ of the direction of the vibration was

¹Given the appropriate probability density function and the 3-D detector adjoints and forward fluxes, Eqs. (1) to (5) could be used to determine the detector response to more complex fuel assembly vibrations (including vibrations with preferred direction).

also assumed to be uniformly distributed over the interval 0 to 2π and only lateral fuel assembly vibrations (in a direction toward or away from the detector) were considered to produce a detector response. With these assumptions, Eq. (5) reduces to

$$E \{ X^2 \} = \frac{\sigma_A^2}{2} \quad (6)$$

where σ_A^2 is the variance of the vibration amplitude. We also assumed that the axial mode shape of the fuel assembly can be described by

$$X(z) = X_0 \sin \frac{\pi z}{H} \quad (7)$$

where

X_0 is the amplitude of vibration at the core center,
 z is the distance from the core bottom, and
 H is the core height.

The Langevin source, Eq. (1), is now expanded to account for changes in particular cross sections. Since water is displaced between the fuel assemblies during vibration, the Langevin source must include changes in the absorption, fission, and scattering cross sections. Therefore, Eq. (1) becomes, in multigroup formulation,

$$\delta S_g = -\delta \Sigma_a^g \phi^g + \sum_{\substack{g'=1 \\ g' \neq g}}^{NG} \delta \Sigma_s^{g' \rightarrow g} \phi^{g'} - \sum_{\substack{g'=1 \\ g' \neq g}}^{NG} \delta \Sigma_s^{g \rightarrow g'} \phi^{g'} + \chi^g \sum_{g'=1}^{NG} \delta \nu \Sigma_f^{g'} \phi^{g'} \quad (8)$$

where

Σ_a = absorption macroscopic cross section,
 Σ_s = scattering macroscopic cross section,
 Σ_f = fission macroscopic cross section,
 χ = fission spectrum,
 ν = number of neutrons emitted per fission,
 g = group number, and
 NG = total number of groups.

For the 1-D calculations we assumed that the flux and detector adjoints were uniform in the transverse directions and that the Langevin sources were 180° out of phase on each side of the assembly.

The following cases for the vibration of a single fuel assembly at the center of the core [case (a)] were studied:

(1) Langevin source with absorption only,

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- (1) Langevin source with absorption only,
- (2) Langevin source including absorption and scattering, and
- (3) Langevin source including absorption, scattering, and fission.

The results, summarized in Table 1, indicate that the predicted detector response is sensitive to all terms of Eq. (8).

TABLE 1 Predicted Ex-Core Neutron Detector Responses for Various Langevin Source Assumptions

Langevin Source Assumption	Ex-Core Detector Response*
Absorption only	4.32×10^{-6}
Absorption + fission	2.25×10^{-6}
Absorption + fission + scattering	1.59×10^{-6}

*Fuel assembly located at the center of the core; vibration amplitude = 2.54×10^{-4} cm. Units are root mean square reaction rate normalized to mean reaction rate (NRMS).

We also calculated the ex-core detector responses expected from the vibration of a single fuel assembly as a function of its position in the core [case (d)]. The results (Table 2) show that a fuel assembly vibrating at the core edge will produce a normalized RMS detector response that is about 60 times larger than would be obtained if the assembly were located at the center of the core.

TABLE 2 Predicted Ex-Core Neutron Detector Responses for Various Fuel Assembly Locations

Fuel Assembly Location (Row)	Ex-Core Detector Response*
1 (core edge)	5.5×10^{-5}
2	1.0×10^{-4}
3	7.5×10^{-5}
4	3.9×10^{-5}
5	1.6×10^{-5}
6	4.9×10^{-6}
7	2.4×10^{-6}
8 (core center)	9.3×10^{-7}

*Vibration amplitude = 2.54×10^{-4} cm; geometry is as shown in Fig. 5. Units are NRMS.

When several fuel assemblies vibrate simultaneously, the ex-core neutron detector response becomes a superposition of the neutron noise induced by each individual fuel assembly. Therefore, the response depends on the cross correlation of the fuel assembly driving forces in a manner described by Mayo (1977). To study this dependence, single fuel assemblies in each of the positions shown in Fig. 5 were assumed to be vibrating simultaneously; adopting a boron concentration of 2100 ppm, a vibration amplitude of 2.54×10^{-4} cm (0.1 mil) RMS, and Langevin sources describing absorption, fission and scattering processes, we calculated the resulting ex-core detector responses. Both spatially correlated (as might occur if core barrel motion were driving fuel assembly vibrations) and spatially uncorrelated (as might result from flow-induced vibrations) driving forces were studied. NRMS response values of 9.55×10^{-5} and 1.43×10^{-4} were obtained for the correlated and uncorrelated cases, respectively. Since the detector response is sensitive to cross terms when spatial correlation is present, response figures were recalculated using the actual number of fuel assemblies in each row of the Sequoyah core. The vibration amplitude was again taken to be 2.54×10^{-4} cm RMS and all the fuel assemblies in a given row were weighted equally by the adjoint and forward fluxes. The resulting ex-core detector responses were found to be 1.16×10^{-3} and 4.79×10^{-4} NRMS for the correlated and uncorrelated cases, respectively. The percent contribution to the total ex-core detector response attributable to simultaneously uncorrelated vibrating fuel assemblies in the various core rows was also computed, as shown in Fig. 9. These results indicate that ~90% of the ex-core detector response is attributable to the motions of the five fuel assembly rows nearest the detector when the vibrations are treated as uncorrelated.

*Vibration amplitude = 2.54×10^{-4} cm; geometry is as shown in Fig. 5. Units are NRMS.

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Fig. 9. Fractional contribution of simultaneous fuel assembly vibrations to the ex-core neutron detector response.

CONCLUSIONS

Uncertainties in the assumptions employed in this analysis (particularly the assumed behavior of the detector adjoints and the forward fluxes in the transverse directions and the effects of control rod positions) suggest caution in applying these calculated detector responses in a quantitative manner. Nevertheless, we believe the methodology to be useful for studying and understanding space-dependent reactor noise sources. Although our studies are not yet complete, we draw the following conclusions:

1. Fixed-source shielding and point-kinetics calculations probably bound the true ex-core detector response to fuel assembly vibrations at 3 Hz, compared to the more realistic space-, frequency-, energy-dependent kinetic calculations. Our calculations indicate that the ex-core neutron detectors are significantly more sensitive to in-core perturbations than predicted by static shielding techniques.
2. One-dimensional calculations tend to overpredict the spatial sensitivity (magnitude of the detector adjoint) of an ex-core detector compared to two-dimensional calculations.
3. The calculated response of an ex-core detector is sensitive to the assumed reactor state (the reactivity, k) and the terms included in the Langevin source formulation.
4. The detector response is also sensitive to the spatial correlation of noise sources.
5. The calculated ex-core detector responses are sensitive to the assumed composition of ex-core materials.

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