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CARDIOGRAMA: A STOCHASTIC, SEMI-EMPIRICAL METHODOLOGY FOR POWER-REACTOR SURVEILLANCE AND DIAGNOSTICS*

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The utilization of stochastic methods (reactor "noise") for power reactor diagnostics and surveillance applications is by now a relatively well-established technique.[1] In this technique, the power spectral density (PSD) of the fluctuations of a specified state variable is often used to define the reactor's "signature" at a given configuration. Typically, this PSD possesses considerable structure as a function of frequency (i.e., peaks and valleys), and these features have been related with various degrees of success to specific causative mechanisms such as fuel element vibrations, core barrel motions, and thermal-hydraulic resonances.[1] These features also form the basis for surveillance methods whereby changes in the structure of the PSD are detected and then correlated with altered plant conditions.

The purpose of the present work is to address the problem of handling efficiently the substantial amount of information involved in the application of reactor surveillance and diagnostics methods. Specifically, a methodology is described for: (a) representing the PSDs parametrically, and (b) detecting changes from the reactor's baseline PSD (normal signature).

To this end, we model the resonances observed in the reactor PSD as arising from pairs of complex conjugate poles in the detector response function G(f). These poles appear at frequencies $f_\lambda = \nu_\lambda + i\mu_\lambda$, where ν_λ is the location of the resonance and μ_λ is its width. The detector response can thus be modeled as

$$G(f) = \sum_{\lambda=1}^{N} \left(\frac{R_\lambda(f)}{i(f-\nu_\lambda)+\mu_\lambda} + \text{c.c.} \right) \tag{1}$$

where $R_\lambda(f)$ are the residues in the partial fraction expansion of G(f) and N is the number of poles necessary to describe the structure of the PSD.

The PSD, $\Phi_{ii}(f)$, is then defined as

$$\Phi_{ii}(f) = G(f)\, G^{*}(f) \tag{2}$$

Insertion of Eq. (1) into (2) yields

$$\Phi_{ii}(f) = \sum_{\lambda=1}^{N} \left\{ \frac{A_\lambda \mu_\lambda + B_\lambda (f-\nu_\lambda)}{(f-\nu_\lambda)^2 + \mu_\lambda^2} + \frac{A_\lambda \mu_\lambda + B_\lambda (f+\nu_\lambda)}{(f+\nu_\lambda)^2 + \mu_\lambda^2} \right\} \tag{3}$$

where the amplitudes A and B are defined by

$$B_\lambda - i A_\lambda = 2 \sum_{\lambda'} \frac{R_\lambda R_{\lambda'}^{*}}{f_{\lambda'}^{*} - f_\lambda} \tag{4}$$

The first term in the right-hand side of Eq. (3) describes a distorted resonance at $f = \nu_\lambda$ due to the appearance of the resonance interference term $B\,(f-\nu_\lambda)$, which changes sign when passing through the resonant frequency. The second term is a nonresonant contribution resulting from the companion complex conjugate pole. We emphasize that (a) no attempt has been made to distinguish between poles from noise sources and those from the reactor response function, and (b) the resonance widths, μ_λ, cannot be taken as the "natural" real parts of the poles, due to instrumental resolution broadening effects. Hence the parametrization (3) must be regarded as a semi-empirical representation of the reactor PSD.

To detect changes in the structure of the reactor signature we utilize the Wald-Wolfowitz Runs Test.[3] This test compares the number of runs, R, (defined as unbroken sequences of points above and below a reference line) obtained from an ordered set of points with an expected value, E(R), and its variance, V(R), derived from a set of randomly distributed points. Hence, the Wald-Wolfowitz test is sensitive to the structure of the data remaining after removal of the fitted structure [Eq. (3)].

Our methodology is based on the following steps: (a) the baseline PSD data are fitted according to the parametrization (3) and a Wald-Wolfowitz test is performed to determine the "background" number of runs, R_o, as well as $E(R_o)$ and $V(R_o)$ for randomly distributed data points; (b) subsequent PSDs are fitted by the same pole structure as the one corresponding to the baseline (with renormalization of amplitudes) and a runs test is performed to ascertain whether the number of runs, R_o, falls within $R_o \pm 2V^{1/2}(R_o)$; (c) those PSDs failing the runs test in step (b) are refitted and a new pole structure is compiled.

This methodology has been implemented in the Fortran IV code CARDIOGRAMA, which includes algorithms for automatic search for peaks in the PSD. Figure 1 shows a CARDIOGRAMA fit to the PSD of a pressure signal from a 1000 MWe PWR. Utilizing this fit as the baseline PSD, sensitivity tests were then performed on simulated anomalous data, which were constructed by altering the pole parameters 1%. These PSD changes, though not visible to the eye, were readily detected by the Wald-Wolfowitz test.

In summary, the program CARDIOGRAMA has been implemented to (a) compile reactor PSDs and classify them on a basis of the number and location of their poles in the frequency domain, and (b) provide an algorithm for rapid, sensitive identification of changes in reactor signatures.

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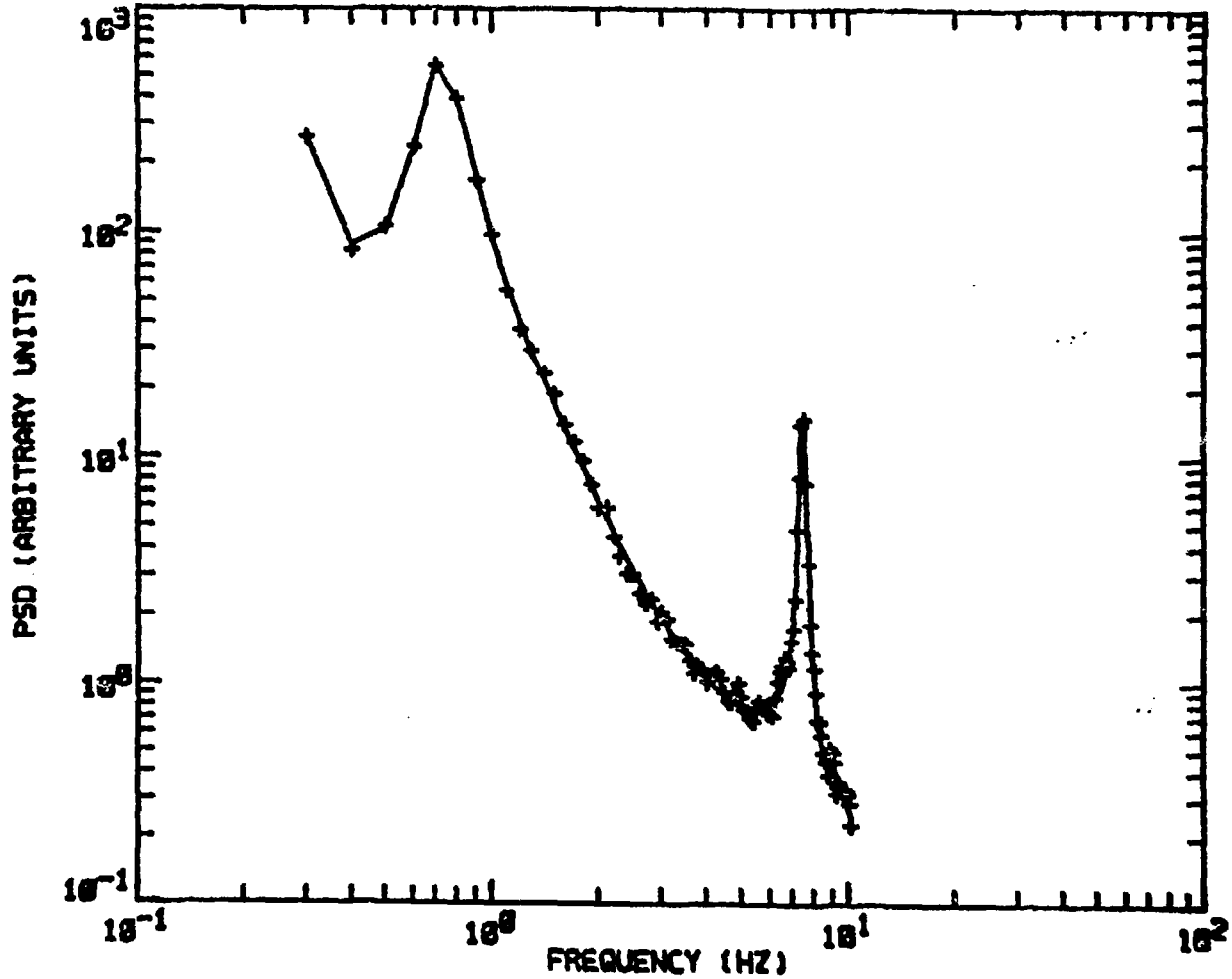
PSD (ARBITRARY UNITS)
FREQUENCY (HZ)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
10^{2}

Figure 1. The points in this figure show the Power Spectral Density (PSD), or a function of frequency, obtained from pressure signal fluctuations in a one thousand MW-electric PWR plant. The continuous line is the functional fit performed on the basis of equation (3) in the text.