IEEE TRANSACTIONS ON

NUCLEAR SCIENCE

OCTOBER 1975 VOLUME NS-22 NUMBER 5

Published Bimonthly

A PUBLICATION OF THE IEEE NUCLEAR AND PLASMA SCIENCES SOCIETY

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Book Reviews

RANDOM PROCESSES IN NUCLEAR REACTORS

by

Michael H. R. Williams

Pergamon Press, Ltd., Oxford, England and New York, 1974, 243 pages, diagrams, 6 x 9 in. Price approx. $28.50

This book is an excellent treatment on mathematical methods applied for usefully interpreting and understanding, by various models, problems in nuclear engineering involving random processes. The central strategy of the author is to establish the analogy between random processes occurring in nuclear reactors and those occurring in other classical fields, particularly in multiplication, branching, and birth-and-death processes, and then to show how the mathematical methods developed in these fields can be extended to deal with analogous problems in nuclear work. In that respect he introduces zero-power, one-velocity, homogenization and point-models approximations, which are developed later to include operating-power, velocity, heterogeneity, and spatial effects.

The book consists of nine chapters, rich in information, each followed by an extensive bibliography.

In the first chapter, the author surveys fields in which random processes arise, such as stochastic differential and integral equations, queing theory, biology, demographic studies, theory of cascade or branching processes, radioactive decay chains, noise phenomena, statistical mechanics, and transport phenomena; and establishes an analogy to neutrons behavior in a reactor. The Boltzmann transport equation for neutrons, based on the idea of molecular caos, is recognized as lacking correlation as an obvious source of noise. The neutrons are interpreted as members of a population subject to multiplication, death and birth processes; and reactor noise phenomena are classified into: (i) zero energy systems, where the focus of attention is the branching process due to fission with its accompanying fluctuations in the number of neutrons per fission, delay times between neuclear events (fission, absorption, or scattering), and the probabilities of occurrence of these events; and (ii) power reactors: where the focus of attention is now the noise arising from mechanical origins (vibration of mechanical parts, boiling of coolant, fluctuations of temperature and pressure), and their associated feedback to the neutronic behavior. The purpose of the analysis is defined as: (i) How to extract the rich dynamic information from the measured noise signals superimposed on the steady background; (ii) How to investigate the causes of randomness; and (iii) How to develop a theory to compare with experiment. "If such an investigation is successful, it would be a significant advance both econically and technically..."

In the second chapter, the Pàl and Bell stochastic Green's function is introduced for zero-power reactors and application of the generating function method for deducing moments (means, variances, and covariances) of the neutrons population is shown. Neutron balance equations are written which lead to differential-difference equations and to partial differential equations for the probability generating function. The conventional point-model equation for reactor kinetics (without delayed neutrons) is deduced by this approach. It is shown how to take into consideration the neutrons precursors and detector shape into consideration.

The third chapter is devoted to uncovering theoretical details which ought to be included in the analysis of certain problems. The author introduces: The Feynman variance-to-mean method where experimental values are fitted to theory for extracting parameters of interest, the auto-correlation and cross-correlation technique (developed in electrical noise measurements), in which, from an apparently random signal one can deduce a deterministic function containing parameters of interest for reactor kinetics studies, the power spectral density method (entailing the Fourier transform of the correlation function) as a measure of the frequency content of the noise spectrum, the Rossi α-technique which leads to a direct measurement of lifetime of reactivity, the sign-correlation techniques, integrated polarity sampling, and the zero-crossings method. The ergodic hypothesis (in a stationary random system time-averages and ensemble-averages are equal), and the experimental implementation of the ideas are very briefly discussed. The limitations of point-reactor models and cases where space and energy dependence and heterogeneity effects must be included in analysis are discussed.

The fourth chapter briefly considers some practical applications, such as the probability of obtaining various neutron density distributions in systems brought to supercriticality, in a number of different ways: such includes weak source start-up in reference to the GODIVA fast critical assembly (and probably to nuclear submarine reactors), the theory of weak source fluctuations, and the extinction probability of fission chains.

Chapter 5 is devoted to the analysis of the Langevin method for noise problems: this is based upon the average equations for the system. Brownian motion, the Gaussian nature of noise, random reactivity perturbations, and the artificial generation of white noise by a pseudo-random signal generator are treated. The Focker-Planck equation is applied to neutron noise via the point-model equations of reactor kinetics with one delayed neutron group. Further discussion of the Langevin technique applied to fission fluctuations is given in an Appendix at the end of the book.

Methods based upon the point-power reactor model for diagnosing existing faults in power reactors, or help predicting these faults before they become serious, are treated in Chapter 6. The statistical nature of many possible reactor noise phenomena: aging process, Xenon poisoning, control-rod movements, delayed neutrons effects, reactor cycle times (e.g.: coolant circulation period), mechanical vibrations, fuel nonuniformity and local heterogeneities, fluctuations in coolant temperature and flow rate, pressure and flow fluctuations in coolant, bubble formation, collapse and entrainment due to pumping, bowing of fuel elements, control-rod movements caused by rough seas, etc... seems to be still unknown. Difficulties of the probability balance method for power reactor noise are discussed. The Langevin technique is used to treat the transfer function between coolant temperature and fuel temperature in a gas-cooled graphite-moderated reactor. From this chapter it appears that noise measurements are clearly useful for detecting mechanical faults: however, before they can be of practical value, it must be shown that they can predict incipient trouble and define its location so that appropriate action can be taken in time. For this to be done effectively, a detailed space-dependent noise theory must be formulated: this is tried in Chapter 7. There, the basic transport equation for the generating function for zero-power reactor noise, with account of delayed neutrons and spatial effects, leads to a set of nonlinear partial differential equations with random parametric excitation. Rational approximations are introduced: such as core homogenization, diffusion approximation to the generating function equation, and infinite-medium analysis.

Techniques, truly representative of actual systems by taking the heterogeneity into effect, are treated in Chapter 8. These are either too difficult to apply, or are not checked out experimentally. The method of Feinberg and Galanin (source-sink method) is used, coupled with heat transfer, fluid flow, and rod vibrations. Some problems relating to power fluctuations due to statistical distributions of fuel particles in pebble-bed reactors, hot spots arising from nonuniform fuel enrichment, random fluctuations in heat transfer coefficients at surfaces and their relation to temperature fluctuations, space-time representation of two-phase flow, random vibrations of fuel elements and control rods are surveyed.

The analysis is concluded in Chapter 9 by some problems not directly of random nature, but affecting reactor behavior randomly: such as the fatigue due to random stresses.

A prior elementary knowledge of neutron transport theory, stochastic processes and nuclear heat transport will make the contents easier to grasp. A wealth of published literature in basic prior work and recent research in the subject are both well-surveyed and referenced: however, account of competing methods for dynamic testing based on small-signal frequency response measurements[1] is omitted: these partly share the advantage of noise analysis techniques in that it is not necessary to shut down the reactor while conducting them, and in that they cause an insignificant interference with power generation. These procedures are entering into routine use for power reactors nowadays, replacing the rod-oscillation techniques.

The theory of zero-power noise seems to be well understood apart from some mathematical details which remain to be solved; however, the noise analysis of operating-power reactors is still in its infancy, due to a lack of understanding of the noise mechanisms involved. As a consequence, "most utilities are still reluctant to accept noise analysis as a day-to-day reactor operation to detect faults such as hot spots or local boiling." However, "the advantages to be gained by reliable noise source measurements in place of the present rod-oscillation techniques and the use of impulsive or ramp disturbances to measure reactor kinetic parameters, are great indeed." We believe that there also exists an excellent prospect for application of these methods in safety and control studies.

The author has done an excellent job in surveying the field and pointing to areas of further research. Accordingly, the book is recommended for design and research scientists and engineers working in different branches of the field and, particularly, for graduate students. A feedback from researchers is needed to aid in implementing noise analysis techniques for routine use by practicing engineers.

The book complements the texts of Thie[2], and Uhrig[3], and it seems that much additional work is still needed towards making the analysis of reactor noise more adaptable, practical and useful for dealing with realistic and real physical situations.

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