Power Reactor Noise

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for the
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Publisher's Foreword

This book, prepared by the American Nuclear Society for the U.S. Nuclear Regulatory Commission, is published as part of ANS's continuing series of monographs on nuclear science and technology.

In the past decade, rapid developments in the field of noise analysis made clear the need for an updated version of Joseph A. Thie's book *Reactor Noise,* which was originally published in 1963—hence, the publication of *Power Reactor Noise.* With new information and an emphasis on power reactors, it is a complete revision of the earlier book.

The general objective of the American Nuclear Society's publishing endeavor is to bring into print information related to nuclear science and technology that will advance the peaceful uses of nuclear energy, as well as satisfy the professional interests of the ANS membership. The American Nuclear Society regards these publishing activities and their contributions to the growing achievements in nuclear energy applications as an essential obligation to the Society membership and the nuclear community.

W. Michael Diekman
Manager, ANS Publications

Preface

The writing of this book was initially envisioned as a substantial revision of my book, *Reactor Noise,* which was originally published in 1963 by Rowman and Littlefield, New York. In drawing upon experience from this specialty's consulting, teaching, publishing, and conference participating, it was found from the material selected that the revision was more than even "substantial." In almost two decades, though mathematical fundamentals remain, many new concepts have arisen. Applications have expanded so much that the entirely new second half of the book now selects examples from power reactor operation; zero-power reactor noise, dominant in the 1963 book, is now a separate specialty well treated in the references given. In the original book, virtually every theoretical and experimental piece of work related to random phenomena in any reactor could be almost individually discussed. Now, a reasonably sized book permits only summarizing representative examples from this ever-expanding technology.

The book is directed to the engineer, scientist, or technician who wishes to perform, interpret, or study various types of diagnostic and surveillance activities in nuclear reactors involving the informative noise content in the process variables' signals. It should, therefore, appeal to (1) power plant personnel involved in testing, instrumentation, and core performance, (2) researchers in reactor and other fields, such as bioengineering and aeronautical and mechanical engineering, for which the examples find analagous applications, (3) administrators and program planners who wish an overview of reactor noise applications, and (4) students of nuclear engineering.

The book is organized into two parts: basic principles and their practical applications. Following an initial chapter on orientation, the early chapters develop the theoretical basis for various methods of noise analysis. It is recognized that analysis may proceed in the time domain or in the frequency domain. For the former, the fundamentals of statistics, correlation, and regression are reviewed, while for the latter Fourier series and related topics are covered. Experimental and theoretical considerations in performing noise tests are developed in succeeding chapters. In the first half of the book, though reactor examples are used extensively, the principles apply to many other fields and may be readily understood by nonreactor technologists.

The last half of the book reviews the many practical applications of noise analysis to specific reactor problems. At-power phenomena within the vessels of water reactors dominate the chapters on neutron, PWR, BWR, and acoustical noise. Extensive use is made of the publications of the world's many reactor noise specialists, including proceedings of several international conferences devoted exclusively to this subject. While the lists of references are quite long, they unfortunately cannot be all-inclusive but at least are hoped to be quite representative.

While a general familiarity with reactors and with higher mathematics is assumed, important concepts are defined and explained as they are introduced throughout the text. Simplistic approaches are used in these explanations with the hope that complex concepts may be easily grasped by nonspecialists.

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Joseph A. Thie

April 1981

Nomenclature

a, a_x, a_y = sine wave amplitude
a_0 = proportionality constant
a_i, a = autoregression parameters; also filter coefficients
A = area
b_i = moving average parameters; also filter coefficients
c = velocity of sound
C, C_x = autocovariance
C_{xy} = cross-covariance
C_j, c_j = number of delayed neutron precursors and deviation of this number from average
D = discriminant for an abnormal noise signature; also the neutron diffusion constant
E = envelope amplitude
f = frequency
f_N = Nyquist frequency
F_0 = fission rate
F, F_0 = force
G, G_0 = reactor transfer function and zero-power reactor transfer function, respectively
G, G_x, G_y = power spectral density
G_{xy} = cross-power spectral density
$G_{xy \cdot z}$ = residual cross-power spectral density
h = enthalpy; also impulse response
H, H_{ik} = transfer function
i = ion-chamber current; also $\sqrt{-1}$
Im [ ] = imaginary part of [ ]
k = local divided by global noise spectrum; also spring constant
k, k_{eff} = neutron multiplication constant
k_p = prompt neutron multiplication constant
K = bulk modulus
ℓ = neutron lifetime
L = thermal neutron migration length
$m, \dot{m}$ = mass and mass flow rate, respectively
m = integer
n = integer or exponent
n, n' = order of autoregression or moving average process, respectively
n = deviation of power from average or any quantity proportional to this
N = rms noise level in the signal-to-noise ratio; also number in a series

N_0 = molecules per gram; also average power or any quantity proportional to this
$\mathfrak{n}$, $\mathfrak{n}_0$ = number of neutrons and average number of neutrons, respectively
p = probability or probability density
P = pressure; also probability of exceeding a value; also power
q = chamber's charge collected per event
r = radial distance
R, R_x = autocorrelation function
R_{xy} = cross-correlation function
Re [ ] = real part of [ ]
s = spatial position variable
S = rms signal level; also source strength; also area variable of integration
t = time
T = temperature
T, T_{data} = data duration in a block of data
T_{tot} = duration of data in all blocks analyzed
v = velocity
W = window weighting function for spectra
x, $\bar{x}$ = random variable and its average value, respectively
X = Fourier amplitude of x
y, $\bar{y}$ = random variable and its average value, respectively
Y = Fourier amplitude of y
z = error function variable; also filtered signal; also vertical distance
α = Rossi alpha; also void fraction
α_{xy} = irreversible circulation
β, β_j = delayed neutron fraction and for just group j, respectively
γ, γ^2 = square root of coherence and coherence, respectively
ε = detector efficiency
ζ = damping constant
θ = angle
λ = wave length of sound; also decay constant
μ = attenuation constant or calibration factor; also mean value
ν = neutrons per fission
ρ = density; also reactivity
ρ, ρ_{xy} = normalized cross-correlation coefficient or function
σ = neutron cross section; also standard deviation
τ = time constant or time lag; also neutron age
τ_c = memory time of system
ϕ = phase angle of transfer function; also neutron flux
ω = angular velocity = $2\pi f$

Contents

1

INTRODUCTION

Meaning of Noise

The term *noise* is commonly used today in many areas of science and engineering. In each it means something different. However, the common ancestor of all these meanings is found in acoustics, where it is used to describe sounds lacking in musical quality. Music is caused by pulsations that, even though complex, are regular or periodic; it is contrasted with acoustical noise, which is irregular or random pulsation. Noise has thus come to mean randomness as distinguished from regularity. The term is generally applicable to any type of signal or information flow.

Random phenomena are very commonly encountered in the sciences. A reactor, which is a rather complex scientific device, can be expected to exhibit noise in a variety of ways. A common type of reactor noise is the random nature of its neutron power. When the neutron population is relatively low, the reactor power can be expected to be rather noisy because the effects of individual neutrons are observed. However, when the neutron population is high, the power can still contain noise, but most likely it is caused by other disturbances. An example of such a disturbance might be the boiling process in a boiling reactor changing the amount of moderator locally and hence changing the local neutron flux.

The signal-to-noise ratio is frequently used as a measure of the noise level. This, along with many other useful concepts in noise theory, originated in electronics and communications. Figure 1-1 shows schematically how the signal-to-noise ratio may be obtained. It is assumed that there is some device that can separate the signal from the noise, though in practice this may sometimes be difficult. The signal-to-noise ratio in decibels is

$$\begin{aligned}\text{number of decibels} &= 10 \log_{10} \frac{\text{signal power}}{\text{noise power}} \\ &= 20 \log_{10} \frac{\text{signal current}}{\text{noise current}} \qquad (1.1)\end{aligned}$$

since electric power is proportional to current squared. The powers re-

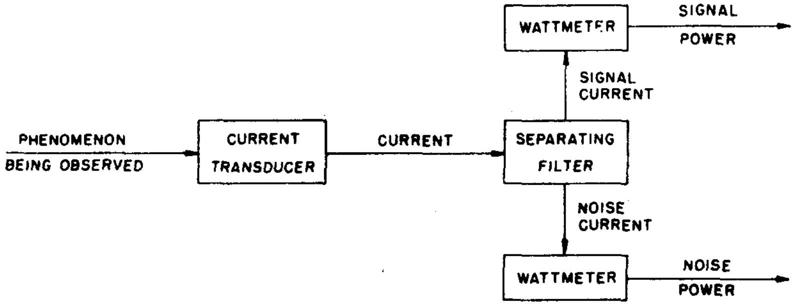

Fig. 1-1. Idealized method of measuring the signal-to-noise ratio.

ferred to are the total ac and dc powers dissipated in the two equal resistors of the two wattmeters. It is common also to speak of signal or noise powers as any quantity that is proportional to these wattmeter readings. An alternative form of Eq. (1.1) is another simply understood measure of noise,

$$\text{percentage noise} = 100 \times \frac{\text{noise current}}{\text{signal current}} . \qquad (1.2)$$

The reactor signal to which the noise is referred to may be simply the average reactor power level. Confusion in nomenclature can arise where the reactor power constitutes the signal or the noise; note in Fig. 1-1 that the signal and noise *information powers* are at the extreme right, while the reactor *thermal power*, in this case, is the phenomenon under observation at the extreme left.

Historical Applications of Noise Analysis

The first published observations of reactor noise were by de Hoffman[1] and subsequently by Courant and Wallace.[2] These works treated zero-power reactor neutron density fluctuations. However, the applications of statistical theory to time-varying processes are quite ancient. An extensive bibliography[3] on this subject cites works as far back as the eighteenth century and cites many specific fields of application within the following general classes:

1. physical and biological sciences
2. economics
3. sociology
4. demography
5. psychological and behavioral sciences.

Within the first of these classes can be found the largest number of applications of statistical methods to time-dependent variables. Technologies in which these are found include acoustics, hydraulics, thermodynamics, mechanics, astronomy, geophysics, meteorology, oceanography, control, aerospace, electronics, communications, chemistry, biology, genetics, medicine, and, of course, power generation, which includes nuclear reactors.

Historically, noise research and development in reactors was restricted to zero-power tests until the late 1950s when Moore,[4] noting analogies to other technologies, pointed out the possibility of obtaining power reactor transfer function information from neutron noise. Experimental work at Argonne National Laboratory,[5] and subsequently at many other laboratories and reactor plants, bore this out—first using only neutron signals, but over the last two decades eventually using many other process variables from the reactor core and other power plant systems.

This development of reactor noise analysis has been treated by books,[6–9] reviews,[10–16] and especially by extensive collections of published papers from several international meetings of reactor noise specialists.[17–23] A partial bibliography, extending only as far as 1971 and restricted to analyses in the time domain (and not including the more prevalent investigations involving the frequency domain), already cites 259 references.[24] Thus, the extensive nature of the literature is quite indicative of the interest displayed in the field of reactor noise applications. This continuing historical interest is also evident in the organizations that exist to study reactor noise. For example, in Japan there has existed for many years a standing Reactor Diagnostics Techniques Research Committee which promotes, in particular, noise research. In Europe over the past decade there has been an annual Informal Noise Meeting of specialists for purposes of unpublished information exchange among researchers from many countries. Also, from time to time, a Specialists Meeting on Reactor Noise[21,22] is sponsored by the Committee on Reactor Physics and the Committee on the Safety of Nuclear Installations within the Organization for Economic Cooperation and Development of the Nuclear Energy Agency.

Techniques of Experimental Reactor Dynamics

Since noise analysis falls within a broad class of experiments that obtain information about reactor dynamics, it may be well to mention some others in this class. These techniques are not necessarily independent of noise methods if experimental conditions cause deterioration in the signal-to-noise ratio.

Experiments in which the reactor is excited by a control rod or valve are popular for obtaining dynamic information. Regarding the former, a step change in rod position gives a reactivity calibration at very low powers, while it gives the reactor response to a step (or ramp) reactivity function at high powers. Transfer function information can be obtained in this manner as well as by other rod motion patterns, such as sinusoidal.[25] Popular patterns are those that are almost random and encompass a wide continuous frequency range at one time.[26]

Reactors that operate at substantial power levels and that are coupled to heat removal equipment can have transients excited in other ways, such as by changes in coolant inlet temperature or flow rate, or changes in system pressure. Actually, any method of varying reactivity is potentially a tool for probing the kinetic behavior of a reactor core—in addition, of course, to related reactor systems. As in the case for control rods, a variety of excitation functions of time may exist.

Table 1-I classifies these approaches to investigating a system's dynamic behavior according to the nature of the analyzed signal. In a nuclear power plant this signal may be the output from any permanently installed or specially added instrument, monitoring any process variable. Deterministic methods, such as excitations by moving a control rod or flow control valve, are the subject of a book[26] primarily devoted to external excitation by pseudorandom signals. The latter consist of on-off states of the input controller with mathematically selected durations so as to give a reasonably uniform distribution of frequencies. On the other hand, *inherently* random

TABLE 1-I

Categories of Dynamic Testing Methods with a Comparison of Reactor Excitation and Inherent Noise Methods

	Dynamic Methods					
	Deterministic				Random	
	Nonperiodic		Periodic			
	Transient	Nonrational Harmonics	One Frequency	Rational Harmonics	Excited	Inherent
Measures transfer function	Yes	Yes				Rarely
Measures power spectrum	No	No				Yes
Cost of experiment	Low	High				Low
Cost of analysis	High	Low				High
Disturbance to reactor	Yes	Yes				No
Typical precision or ability to measure desired frequency band	Medium	High				Medium

signals, the subject of this book, necessarily depend on natural processes within the reactor for whatever distribution of frequency content these make available for measurement.

Some generalizations are made in Table 1-I in comparing analysis of inherently random signals with continuous excitation methods. These obviously represent typical and not universally applicable assessments; in certain instances, quantitative evaluations of the two approaches could lead to other comparative results.

Reasons for Noise Analysis

Table 1-II lists the pros and cons of reactor testing/monitoring involving the analysis of unexcited, inherently random signals. An attempt is made to separate out reasons intrinsic within these noise tests from those reasons that generically pertain to both these and any other type of testing or monitoring activity. Among the more important reasons favoring any reactor dynamics investigation activity should be the ability to make a

TABLE 1-II

Reasons For and Against Reactor Tests in General and Noise Tests in Particular

Reasons For	Reasons Against
Research	Fear of an induced shutdown
Training	Expenditure of time and money
Diagnosis	Redundant with another test
Specific measurement	Rather not know about a problem and thereby avoid criticisms for misjudging actions test might require
Safety/legal requirement or "credit"	Desire for an immediate fix
Substitute for another test or inspection	
Following a precedent	
Design or model verification	
Natural multivariable interactions[a]	Better alternative[a]
Early warnings by continuous monitoring[a]	Risk of data misinterpretation[a]
Simplicity[a]	Limited appreciation of capabilities of method[a]
Low cost[a]	Accuracy limits[a]
No interference with operating policy[a]	Inadequate inherent noise source strength[a]
Obtaining "signatures," i.e., empirical noise descriptors[a]	Deficiency in a noise model or its parameters[a]
	Little history or precedent[a]
	Instrumentation difficulties[a]

[a] Particularly applicable to noise tests.