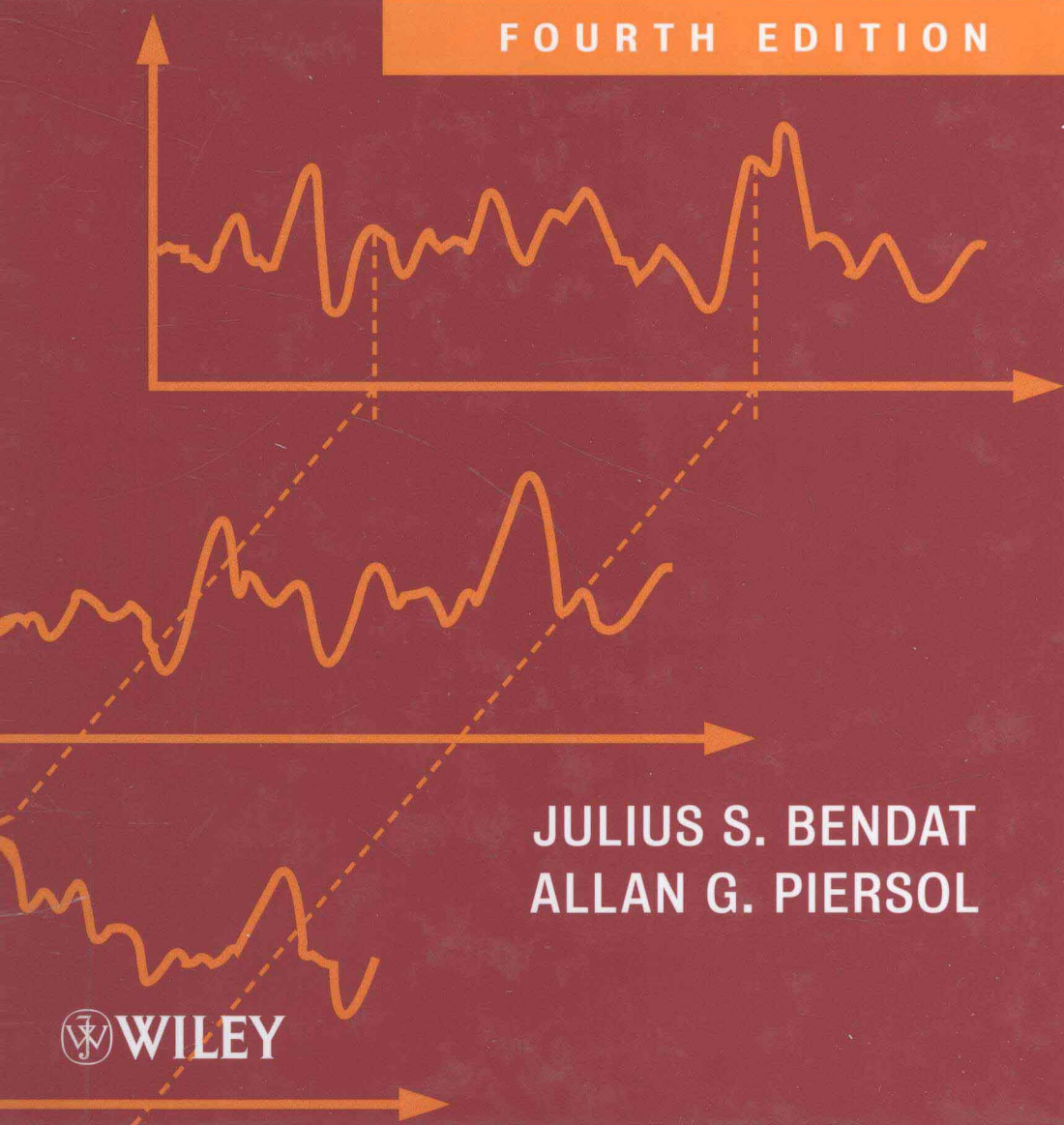


RANDOM DATA

Analysis and Measurement Procedures

FOURTH EDITION



**JULIUS S. BENDAT
ALLAN G. PERSOL**

 **WILEY**

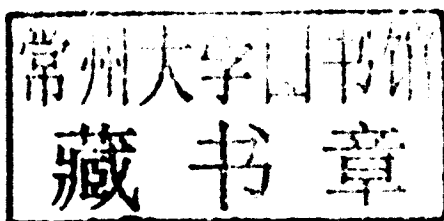
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Fourth Edition

JULIUS S. BENDAT

ALLAN G. PERSOL



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To Allan G. Piersol
1930-2009

Preface

This book is dedicated to my coauthor, Allan G. Piersol, who died on March 1, 2009. I met Allan in 1959 when we were both working at Ramo-Wooldridge Corporation in Los Angeles. I had just won a contract from Wright-Patterson Air force Base in Dayton, Ohio, to study the application of statistics to flight vehicle vibration problems. I was familiar with statistical techniques but knew little about aircraft vibration matters. I looked around the company and found Allan who had previous experience from Douglas Aircraft Company in Santa Monica on testing and vibration problems. This started our close association together that continued for 50 years.

In 1963, I left Ramo-Wooldridge to become an independent mathematical consultant and to form a California company called Measurement Analysis Corporation. I asked Allan to join me where I was the President and he was the Vice President. Over the next 5 years until we sold our company, we grew to 25 people and worked for various private companies and government agencies on aerospace, automotive, oceanographic, and biomedical projects. One of our NASA projects was to establish requirements for vibration testing of the Saturn launch vehicle for the Apollo spacecraft to send men to the moon and return them safely to earth. Allan was a member of the final certification team to tell Werner Von Braun it was safe to launch when the Apollo mission took place in 1969.

In 1965, Allan and I were invited by the Advanced Group on Aeronautical Research and Development of NATO to deliver a one-week series of lectures at Southampton University in England. Some 250 engineers from all over Europe attended this event. Preparation for these lectures led to our first book *Measurement and Analysis of Random Data* that was published by John Wiley and Sons in 1966. This first book filled a strong need in the field that was not available from any other source to help people concerned with the acquisition and analysis of experimental physical data for engineering and scientific applications. From further technical advances and experience by others and us, we wrote three updated editions of this *Random Data* book published by Wiley in 1971, 1986, and 2000. We were also able to write two companion books *Engineering Applications of Correlation and Spectral Analysis* published by Wiley in 1980 and 1993.

In all of our books, Allan and I carefully reviewed each other's work to make the material appear to come from one person and to be clear and useful for readers. Our books have been translated into Russian, Chinese, Japanese, and Polish and have had world sales to date of more than 100,000 copies. We traveled extensively to do consulting work on different types of engineering research projects, and we gave many educational short courses to engineering companies, scientific meetings, universities, and government agencies in the United States as well as in 25 other countries.

The preface to the third edition and the contents should be read to help understand and apply the comprehensive material that appears in this book. Chapters 1–6 and Chapter 12 in this fourth edition are the same as in the third edition except for small corrections and additions. Chapters 7–11 contain new important technical results on mathematical formulas and practical procedures for random data analysis and measurement that replace some previous formulas and procedures in the third edition. Chapter 13 now includes a computer-generated Hilbert transform example of engineering interest. Chapter 14, Nonlinear System Analysis, is a new chapter that discusses recommended techniques to model and identify the frequency-domain properties of large classes of nonlinear systems from measured input/output random data. Previous editions deal only with the identification of linear systems from measured data.

This fourth edition of *Random Data* from 50 years of work is our final contribution to the field that I believe will benefit students, engineers, and scientists for many years.

JULIUS S. BENDAT

Los Angeles, California
January 2010

Preface to the Third Edition

This new third edition of *Random Data: Analysis and Measurement Procedures* is the third major revision of a book originally published by Wiley in 1966 under the title *Measurement and Analysis of Random Data*. That 1966 book was based upon the results of comprehensive research studies that we performed for various agencies of the United States government, and it was written to provide a reference for working engineers and scientists concerned with random data acquisition and analysis problems. Shortly after its publication, computer programs for the computation of complex Fourier series, commonly referred to as fast Fourier transform (FFT) algorithms, were introduced that dramatically improved random data analysis procedures. In particular, when coupled with the increases in speed and decreases in cost of digital computers, these algorithms led to traditional analog data analysis instruments being replaced by digital computers with appropriate software. Hence, in 1971, our original book was extensively revised to reflect these advances and was published as a first edition under the present title.

In the mid-1970s, new iterative algorithms were formulated for the analysis of multiple-input/output problems that substantially enhanced the ability to interpret the results of such analyses in a physically meaningful way. This fact, along with further advances in the use of digital computers plus new techniques resulting from various projects, led to another expansion of our book that was published in 1986 as the second edition. Since 1986, many additional developments in random data measurement and analysis procedures have occurred, including (a) improvements in data acquisition instruments, (b) modified iterative procedures for the analysis of multiple-input/output problems that reduce computations, and (c) practical methods for analyzing nonstationary random data properties from single sample records. For these and other reasons, this book has again been extensively revised to produce this third edition of *Random Data*.

The primary purpose of this book remains the same, namely, to provide a practical reference for working engineers and scientists in many fields. However, since the first publication in 1966, this book has found its way into a number of university classrooms as a teaching text for advanced courses on the analysis of random processes. Also, a different companion book written by us entitled *Engineering*

Applications of Correlation and Spectral Analysis, published by Wiley–Interscience in 1980 and revised in a second edition in 1993, includes numerous illustrations of practical applications of the material in our 1971 and 1986 books. This has allowed us in the third edition of *Random Data* to give greater attention to matters that enhance its use as a teaching text by including rigorous proofs and derivations of more of the basic relationships in random process theory that are difficult to find elsewhere.

As in the second edition, Chapters 1, 2, and 4 present background material on descriptions of data, properties of linear systems, and statistical principles. Chapter 3 on probability fundamentals has been revised and expanded to include formulas for the Rayleigh distribution and for higher order changes of variables. Chapter 5 presents a comprehensive discussion of stationary random process theory, including new material on wavenumber spectra and on level crossings and peak values of normally distributed random data. Chapters 6 and 7 develop mathematical relationships for the detailed analysis of single-input/output and multiple-input/output linear systems that include modified algorithms. Chapters 8 and 9 derive important practical formulas to determine statistical errors in estimates of random data parameters and linear system properties from measured data. Chapter 10 on data acquisition and processing has been completely rewritten to cover major changes since the publication of the second edition. Chapter 11 on data analysis has been updated to include new approaches to spectral analysis that have been made practical by the increased capacity and speed of digital computations. Chapter 12 on nonstationary data analysis procedures has been expanded to cover recent advances that are applicable to single sample records. Chapter 13 on the Hilbert transform remains essentially the same.

We wish to acknowledge the contributions to this book by many colleagues and associates, in particular, Paul M. Agabian, Robert N. Coppolino, and Robert K. Otnes, for their reviews of portions of the manuscript and helpful comments. We also are grateful to the many government agencies and industrial companies that have supported our work and sponsored our presentation of short courses on these matters.

JULIUS S. BENDAT
ALLAN G. PERSOL

Los Angeles, California
January 2000

Glossary of Symbols

| | |
|--------------------------|---|
| a, b | Sample regression coefficients, arbitrary constants |
| A | Amplitude, reverse arrangements, regression coefficient |
| $A(f)$ | Frequency response function after linear or nonlinear operation |
| $b[]$ | Bias error of [] |
| B | Cyclical frequency bandwidth, regression coefficient |
| B_e | Frequency resolution bandwidth |
| B_n | Noise spectral bandwidth |
| B_s | Statistical bandwidth |
| c | Mechanical damping coefficient, arbitrary constant |
| C | Electrical capacitance |
| C_{xy} | Covariance |
| $C_{xx}(\tau)$ | Autocovariance function |
| $C_{xy}(\tau)$ | Cross-covariance function |
| $C_{xy}(f)$ | Coincident spectral density function (one-sided) |
| $e(t)$ | Potential difference |
| $E[]$ | Expected value of [] |
| f | Cyclical frequency |
| Δf | Bandwidth resolution (Hz) |
| $\mathcal{F}[]$ | Fourier transform of [] |
| $G_{xx}(f)$ | Autospectral density function (one-sided) |
| $G_{xy}(f)$ | Cross-spectral density function (one-sided) |
| $G_{yy x}(f)$ | Conditioned autospectral density function (one-sided) |
| $G_{x_i y \cdot x_j}(f)$ | Conditioned cross-spectral density function (one-sided) |
| $G(\kappa)$ | Wavenumber spectral density function (one-sided) |
| $\mathcal{G}(f)$ | “Energy” spectral density function |
| $h(\tau)$ | Unit impulse response function |
| $H(f)$ | Frequency response function |
| $ H(f) $ | System gain factor |
| $\mathcal{H}[]$ | Hilbert transform of [] |
| i | Index |
| $i(t)$ | Current |
| $\text{Im}[]$ | Imaginary part of [] |
| j | $\sqrt{-1}$, index |

| | |
|--------------------------|--|
| k | Mechanical spring constant, index |
| K | Number of class intervals |
| L | Electrical inductance, length |
| $L(f)$ | Frequency response function for conditioned inputs |
| m | Mechanical mass, maximum number of lag values |
| n | Degrees of freedom, index |
| N | Sample size, number of sample records |
| $p(x)$ | Probability density function |
| $p(x, y)$ | Joint probability density function |
| $P(x)$ | Probability distribution function |
| $P(x, y)$ | Joint probability distribution function |
| Prob[] | Probability that [] |
| PSNR | Peak signal-to-noise ratio |
| PS/N | Peak signal-to-noise ratio in dB |
| q | Number of inputs |
| $q(t)$ | Electrical charge |
| $q(R)$ | Rayleigh probability density function |
| $Q(R)$ | Rayleigh probability distribution function |
| $Q_{xy}(f)$ | Quadrature spectral density function (one-sided) |
| r | Number of outputs, number of lag values |
| r_{xy} | Sample correlation coefficient |
| R | Electrical resistance |
| $R(t)$ | Envelope function |
| $R_{xx}(\tau)$ | Autocorrelation function |
| $R_{xy}(\tau)$ | Cross-correlation function |
| $R(t_1, t_2)$ | Double-time correlation function |
| $\mathcal{R}(\tau, t)$ | Alternate double-time correlation function |
| Re[] | Real part of [] |
| s | Sample standard deviation |
| s^2 | Sample variance |
| s_{xy} | Sample covariance |
| s.d.[] | Standard deviation of [] |
| $S_{xx}(f)$ | Autospectral density function (two-sided) |
| $S_{xy}(f)$ | Cross-spectral density function (two-sided) |
| $S_{yy \cdot x}(f)$ | Conditioned autospectral density function (two-sided) |
| $S_{x_i y \cdot x_j}(f)$ | Conditioned cross-spectral density function (two-sided) |
| $\mathcal{S}(f)$ | “Energy” spectral density function (two-sided) |
| $S(f_1, f_2)$ | Double-frequency spectral density function (two-sided) |
| $\mathcal{S}(f, g)$ | Alternate double-frequency spectral density function (two-sided) |
| SNR | Signal-to-noise ratio |
| S/N | Signal-to-noise ratio in dB |
| SG(f, t) | Spectrogram |
| t | Time variable, Student t variable |
| Δt | Sampling interval |
| T | Record length |

| | |
|-----------------------------------|--|
| T_n | Noise correlation duration |
| T_r | Total record length |
| u_n | Raw data values |
| $u(t), v(t)$ | Time-dependent variables |
| $\text{Var } []$ | Variance of [] |
| W | Amplitude window width |
| $W(f, t)$ | Frequency-time spectral density function (one-sided) |
| $\mathcal{W}(f, t)$ | Frequency-time spectral density function (two-sided) |
| $WD(f, t)$ | Wigner distribution |
| $x(t), y(t)$ | Time-dependent variables |
| \bar{x} | Sample mean value of x |
| x^2 | Sample mean square value of x |
| $\tilde{x}(t)$ | Hilbert transform of $x(t)$ |
| X | Amplitude of sinusoidal $x(t)$ |
| $X(f)$ | Fourier transform of $x(t)$ |
| $X(f, T)$ | Fourier transform of $x(t)$ over record length T |
| z | Standardized normal variable |
| $ [] $ | Absolute value of [] |
| $[\wedge]$ | Estimate of [] |
| α | A small probability, level of significance, dummy variable |
| β | Probability of a type II error, dummy variable |
| $\gamma_{xy}^2(f)$ | Ordinary coherence function |
| $\gamma_{y:x}^2(f)$ | Multiple coherence function |
| $\gamma_{x_{ij}y \cdot x_j}^2(f)$ | Partial coherence function |
| δ | Spatial variable |
| $\delta()$ | Delta function |
| Δ | Small increment |
| ε | Normalized error |
| κ | Wavenumber |
| λ | Wavelength |
| θ | Phase angle |
| $\theta_{xy}(f)$ | Argument of $G_{xy}(f)$ |
| μ | Mean value |
| ρ | Correlation coefficient |
| $\rho(\tau)$ | Correlation coefficient function |
| σ | Standard deviation |
| σ^2 | Variance |
| τ | Time displacement |
| $\phi(f)$ | Phase factor |
| ϕ | Arbitrary statistical parameter |
| χ^2 | Statistical chi-square variable |
| ψ | Root mean square value |
| ψ^2 | Mean square value |
| ζ | Mechanical damping ratio |

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