

Signals, Systems & Inference

GLOBAL EDITION

ALAN V. OPPENHEIM & GEORGE C. VERCHESE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



Signals, Systems and Inference, Global Edition

Table of Contents

F	r۸	nt	C.c	ve	r

Title page

Copyright page

Contents

Preface

The Cover

Acknowledgments

Prologue

- 1. Signals and Systems
 - 1.1 Signals, Systems, Models, and Properties
 - 1.1.1 System Properties
 - 1.2 Linear, Time-Invariant Systems
 - 1.2.1 Impulse-Response Representation of LTI Systems
 - 1.2.2 Eigenfunction and Transform Representation of LTI Systems
 - 1.2.3 Fourier Transforms
 - 1.3 Deterministic Signals and Their Fourier Transforms
 - 1.3.1 Signal Classes and Their Fourier Transforms
 - 1.3.2 Parsevals Identity, Energy Spectral Density, and Deterministic Autocorrelation
 - 1.4 Bilateral Laplace and Z-Transforms
 - 1.4.1 The Bilateral z -Transform
 - 1.4.2 The Bilateral Laplace Transform



1.5 Discrete-Time Processing of Continuous-Time Signals

- 1.5.1 Basic Structure for DT Processing of CT Signals
- 1.5.2 DT Filtering and Overall CT Response
- 1.5.3 Nonideal D/C Converters

1.6 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

2. Amplitude, Phase, and Group Delay

- 2.1 Fourier Transform Magnitude and Phase
- 2.2 Group Delay and the Effect of Nonlinear Phase
 - 2.2.1 Narrowband Input Signals
 - 2.2.2 Broadband Input Signals
- 2.3 All-Pass and Minimum-Phase Systems
 - 2.3.1 All-Pass Systems
 - 2.3.2 Minimum-Phase Systems
- 2.4 Spectral Factorization
- 2.5 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

3. Pulse Amplitude Modulation

- 3.1 Baseband Pulse-Amplitude Modulation
 - 3.1.1 The Transmitted Signal
 - 3.1.2 The Received Signal
 - 3.1.3 Frequency-Domain Characterizations



- 3.1.4 Intersymbol Interference at the Receiver
- 3.2 Nyquist Pulses
- 3.3 Passband Pulse-Amplitude Modulation
 - 3.3.1 Frequency-Shift Keying (FSK)
 - 3.3.2 Phase-Shift Keying (PSK)
 - 3.3.3 Quadrature Amplitude Modulation (QAM)
- 3.4 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

4. State-Space Models

- 4.1 System Memory
- 4.2 Illustrative Examples
- 4.3 State-Space Models
 - 4.3.1 DT State-Space Models
 - 4.3.2 CT State-Space Models
 - 4.3.3 Defining Properties of State-Space Models
- 4.4 State-Space Models from LTI Input-Output
- 4.5 Equilibria and Linearization of Nonlinear State-Space Models
 - 4.5.1 Equilibrium
 - 4.5.2 Linearization
- 4.6 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

5. LTI State-Space Models



- 5.1 Continuous-Time and Discrete-Time LTI Models
- 5.2 Zero-Input Response and Modal Representation
 - 5.2.1 Undriven CT Systems
 - 5.2.2 Undriven DT Systems
 - 5.2.3 Asymptotic Stability of LTI Systems
- 5.3 General Response in Modal Coordinates
 - 5.3.1 Driven CT Systems
 - 5.3.2 Driven DT Systems
 - 5.3.3 Similarity Transformations and Diagonalization
- 5.4 Transfer Functions, Hidden Modes, Reachability, and Observability
 - 5.4.1 Input-State-Output Structure of CT Systems
 - 5.4.2 Input-State-Output Structure of DT Systems
- 5.5 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

- 6. State Observers and State Feedback
 - 6.1 Plant and Model
 - 6.2 State Estimation and Observers
 - 6.2.1 Real-Time Simulation
 - 6.2.2 The State Observer
 - 6.2.3 Observer Design
 - 6.3 State Feedback Control
 - 6.3.1 Open-Loop Control
 - 6.3.2 Closed-Loop Control via LTI State Feedback
 - 6.3.3 LTI State Feedback Design
 - 6.4 Observer-Based Feedback Control



6.5 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

7. Probabilistic Models

- 7.1 The Basic Probability Model
- 7.2 Conditional Probability, Bayes Rule, and Independence
- 7.3 Random Variables
- 7.4 Probability Distributions
- 7.5 Jointly Distributed Random Variables
- 7.6 Expectations, Moments, and Variance
- 7.7 Correlation and Covariance for Bivariate Random Variables
- 7.8 A Vector-Space Interpretation of Correlation Properties
- 7.9 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

8. Estimation

- 8.1 Estimation of a Continuous Random Variable
- 8.2 From Estimates to the Estimator
 - 8.2.1 Orthogonality
- 8.3 Linear Minimum Mean Square Error Estimation
 - 8.3.1 Linear Estimation of One Random Variable from a Single Measurement of Anot
 - 8.3.2 Multiple Measurements
- 8.4 Further Reading



Problems

Basic Problems

Advanced Problems

Extension Problems

9. Hypothesis Testing

- 9.1 Binary Pulse-Amplitude Modulation in Noise
- 9.2 Hypothesis Testing with Minimum Error Probability
 - 9.2.1 Deciding with Minimum Conditional Probability of Error
 - 9.2.2 MAP Decision Rule for Minimum Overall Probability of Error
 - 9.2.3 Hypothesis Testing in Coded Digital Communication
- 9.3 Binary Hypothesis Testing
 - 9.3.1 False Alarm, Miss, and Detection
 - 9.3.2 The Likelihood Ratio Test
 - 9.3.3 NeymanPearson Decision Rule and Receiver Operating Characteristic
- 9.4 Minimum Risk Decisions
- 9.5 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

10. Random Processes

- 10.1 Definition and Examples of a Random Process
- 10.2 First-and Second-Moment Characterization of Random Processes
- 10.3 Stationarity
 - 10.3.1 Strict-Sense Stationarity
 - 10.3.2 Wide-Sense Stationarity



10.3.3 Some Properties of WSS Correlation and Covariance Functions

10.4 Ergodicity

10.5 Linear Estimation of Random Processes

10.5.1 Linear Prediction

10.5.2 Linear FIR Filtering

10.6 LTI Filtering of WSS Processes

10.7 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

11. Power Spectral Density

11.1 Spectral Distribution of Expected Instantaneous Power

- 11.1.1 Power Spectral Density
- 11.1.2 Fluctuation Spectral Density
- 11.1.3 Cross-Spectral Density

11.2 Expected Time-Averaged Power Spectrum and the Einstein-Wiener-KhinchinTheorem

11.3 Applications

- 11.3.1 Revealing Cyclic Components
- 11.3.2 Modeling Filters
- 11.3.3 Whitening Filters
- 11.3.4 Sampling Bandlimited Random Processes

11.4 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems



12. Signal Estimation

- 12.1 LMMSE Estimation for Random Variables
- 12.2 FIR Wiener Filters
- 12.3 The Unconstrained DT Wiener Filter
- 12.4 Causal DT Wiener Filtering
- 12.5 Optimal Observers and Kalman Filtering
 - 12.5.1 Causal Wiener Filtering of a Signal Corrupted by Additive Noise
 - 12.5.2 Observer Implementation of the Wiener Filter
 - 12.5.3 Optimal State Estimates and Kalman Filtering
- 12.6 Estimation of CT Signals
- 12.7 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

13. Signal Detection

- 13.1 Hypothesis Testing with Multiple Measurements
- 13.2 Detecting a Known Signal in I.I.D. Gaussian Noise
 - 13.2.1 The Optimal Solution
 - 13.2.2 Characterizing Performance
 - 13.2.3 Matched Filtering

13.3 Extensions of Matched-Filter Detection

- 13.3.1 Infinite-Duration, Finite-Energy Signals
- 13.3.2 Maximizing SNR for Signal Detection in White Noise
- 13.3.3 Detection in Colored Noise
- 13.3.4 Continuous-Time Matched Filters
- 13.3.5 Matched Filtering and Nyquist Pulse Design
- 13.3.6 Unknown Arrival Time and Pulse Compression



13.4 Signal Discrimination in I.I.D. Gaussian Noise

13.5 Further Reading

Problems

Basic Problems

Advanced Problems

Extension Problems

Bibliography

Index

Back Cover

