SIGNALS and SYSTEMS PRIMER with MATLAB®

THE ELECTRICAL ENGINEERING AND APPLIED SIGNAL PROCESSING SERIES

Edited by Alexander Poularikas

The Advanced Signal Processing Handbook: Theory and Implementation for Radar, Sonar, and Medical Imaging Real-Time Systems
Stergios Stergiopoulos

The Transform and Data Compression Handbook
K.R. Rao and P.C. Yip

Handbook of Multisensor Data Fusion
David Hall and James Llinas

Handbook of Neural Network Signal Processing
Yu Hen Hu and Jenq-Neng Hwang

Handbook of Antennas in Wireless Communications
Lal Chand Godara

Noise Reduction in Speech Applications
Gillian M. Davis

Signal Processing Noise
Vyacheslav P. Tuzlukov

Digital Signal Processing with Examples in MATLAB®
Samuel Stearns

Applications in Time-Frequency Signal Processing
Antonia Papandreou-Suppappola

The Digital Color Imaging Handbook
Gaurav Sharma

Pattern Recognition in Speech and Language Processing
Wu Chou and Biing-Hwang Juang

Propagation Handbook for Wireless Communication System Design
Robert K. Crane

Nonlinear Signal and Image Processing: Theory, Methods, and Applications
Kenneth E. Barner and Gonzalo R. Arce

Smart Antennas
Lal Chand Godara

Mobile Internet: Enabling Technologies and Services
Apostolis K. Salkintzis and Alexander Poularikas

Soft Computing with MATLAB®
Ali Zilouchian

Wireless Internet: Technologies and Applications
Apostolis K. Salkintzis and Alexander Poularikas

Signal and Image Processing in Navigational Systems
Vyacheslav P. Tuzlukov

Medical Image Analysis Methods
Lena Costaridou

MIMO System Technology for Wireless Communications
George Tsoulos

Signals and Systems Primer with MATLAB®
Alexander Poularikas

SIGNALS and SYSTEMS PRIMER with MATLAB®

Alexander D. Poularikas

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2007 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Version Date: 20130916

International Standard Book Number-13: 978-1-4200-0695-7 (eBook - PDF)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (http://www.copyright.com/) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

To our grandchildren Colton-Alexander and Thatcher-James who have given us so much pleasure and happiness and have shown us how difficult it is to teach a time-varying, nonlinear, noncausal, and a multiple-input–multiple-output (MIMO) feedback system.

Preface

Signals and Systems is designed for use as a one-semester analog track, a one-semester digital track, a one-semester analog–digital track, or a two-semester analog–digital course.

We have included several carefully chosen examples from many fields to show the wide applicability of the material and methods presented in this text. The selection of examples from diverse engineering fields, as well as from nonengineering fields, helps to motivate and excite the student to delve into this course with enthusiasm. It is important that the student studies and learns the material presented, since this course is one of the most fundamental in the electrical engineering curriculum. To illustrate this diversity, the examples we include are drawn from chemical engineering, mechanical engineering, biomedical engineering, process control, economics, heat transfer, and other areas. They show that systems in general possess two features: the input signals to the system are functions of one or more independent variables, and the systems produce signals when excited by input signals. It is well known that engineers in their long careers will face problems that are not purely electrical engineering. They will be involved in heating problems of their electronic chips, the use of electromechanical elements driven by small motors in the development of disc drives, the modeling of parts of the body when helping biomedical engineers, the development of edge detectors when involved in pattern recognition of targets, and numerous other applications.

It is the author's belief that a good background, first of analog signals and systems, is necessary for the study of discrete signals and systems. It is known that discrete signals do not exist in nature for the simple fact that their detection needs the use of a physical transducer. Therefore, introducing arbitrarily the signal $x(n)$, which is derived from the continuous signal $x(t)$ by taking its values at equal time distances T, it is difficult for the student to understand why $x(n)$ and $x(t)$ are two different signals. Furthermore, unless the student is well versed and has a good knowledge of the spectrum of analog signals, he or she will have difficulties understanding the spectrum of sampled signals. Some methods to build digital filters are based on analog filter considerations and use.

In this text we have strived to balance the modeling and presentation of systems and their interaction with signals, as well as the study of signals.

We have tried to balance these two entities and avoid the presentation of a couple of systems, based on electrical circuits alone, for example, and then proceed to deal only with signals and their interaction with system models arbitrarily given without deriving them. It is important that the student be able to create the mathematical representation of a system from the physical laws that govern it, its physical presentation, and its underline constants. Engineers, if they want to be creative, must be able to model accurately the systems they investigate and find their responses under many different excitations. This type of work is at the heart of the engineering field.

The electrical engineering field, as it was taught for a long time based on electrical notion, has been changed considerably. For example, microelectromechanical systems (MEMS) are part of the electrical engineering study today and include mechanical systems, signal processing, mathematics, solid-state physics, vibration analysis (deterministic and random), etc. The above discussion points to the fact that electrical engineering students must possess a wide variety of knowledge in many fields. The engineers must be able to build and study systems and predict results accurately. This book tries to do that by introducing systems from many diverse disciplines.

In the beginning, we introduce the block diagram presentation of systems, starting from the most elementary systems represented by one element, such as resistors, capacitors, mass, etc. This approach starts the student in the right direction so that he or she builds the right foundation. During their career, engineers will deal with block diagram representations of complicated and interrelated systems and will be expected to produce the right solution.

In this text, by expounding and covering continuous and discrete systems, we try to emphasize that some operations are done by computer software, and therefore we are talking about software systems. It is important for the student to realize that circuits, mechanical control systems, and physical media and computers are the everyday compound systems found in most of the devices in the market.

Because coverage of the different fields starts from the fundamental laws and devices, there is an additive flexibility, and the book can be used in other fields of engineering with equal ease. The prerequisites for this course are the standard mathematics and engineering courses up to the junior year.

In this text, we have also introduced advanced concepts in their elementary form such that students require the fundamentals of those principles that will become the basis for their future studies. Concepts such as correlation, match filtering, least squares estimation, adaptation, edge detection, etc., are skillfully introduced so that the student builds his or her knowledge on these important signal processing procedures. Furthermore, although new situations and systems are studied, we require their presentations and solutions to use methods already introduced, such as spectra, convolution, impulse response, etc. This repetition is one of the most basic pedagogical methods of learning available in the field of education.

The modeling of signals and systems is inherently mathematical and involves mathematical forms not ordinarily studied by undergraduate engineering majors. Therefore, to improve the student's skills in different fields of needed mathematics, we have included enough mathematical material to serve in understanding the classical solution of differential and difference equations, convolutions and correlations, Fourier transforms, z-transforms, and other important topics. For the same purpose, we have also included as appendices mathematical formulas, definitions, algebraic summations, etc.

We have introduced MATLAB functions and m-files to produce the desired results. We have not introduced SIMULINK or any other canned software program because we feel, at this early learning stage, that the student should program the steps needed to find his or her answer. With this form of programming, the student must first understand the problem, understand the necessary steps in the digital format, find the requested results, and, finally, compare them with the corresponding mathematical results whenever they exist. Educators should refrain from canned programs. Very often, even in my graduate classes, when we learn about Fourier transforms and ask the students to obtain the transform of a finite signal using computers, they come with plots in the frequency domain from 0 to ½, although we have emphasized in class that every finite signal has infinite spectrum. When asked what 0 to ½ means in the frequency axis, the answer is that MATLAB gave it to them in this form. In my undergraduate classes, I explain to the students the history and importance of the fast Fourier transform (FFT), but I require that they find the discrete Fourier transform (DFT) from the definition.

Pedagogical features

1. The book introduces all the needed mathematical background within the chapters; some additional material is included in the appendices.
2. There is a balance between signals and systems, and both are emphasized equally.
3. Examples are derived from many diverse fields to emphasize that this course is applicable to any field as long as the systems are characterized by the same form of mathematical equations.
4. Key equations are boxed to emphasize their importance.
5. There are examples in the text and problems. In addition, appendices are also added in some chapters to elucidate the mathematics of the chapter.
6. We use paragraphs with the indication "**Note**" to emphasize the meaning of a concept or to improve the understanding of an operation.
7. Analog and digital signal processing and systems are presented in separate chapters. From experience, we have found that students get confused easily by jumping back and forth between analog and digital. It may seem appropriate and even novel for an experienced

person, but for a student that is meeting many of these concepts and mathematical areas for the first time, it is rather confusing.

8. We strive to repeat introduced concepts, such as convolution, correlation, spectra, etc., throughout the book. Repetition is the most fundamental pedagogical learning process, and in this book we try to use it.
9. The author believes that at an early stage of an engineering student's career, exposure to random signals and their interaction with linear time-invariant (LTI) systems is essential. There is nothing deterministic in the physical world. Most students in their professional life will deal with and study random phenomena, such as earthquake signals, electroencephalograms, thermal noise in electrical elements, noise introduced during the transportation of signals through different communication channels, radar returns, target recognition, acoustic signals in the ocean, etc. For this reason, Chapter 13 was added.
10. It is very important that our undergraduate students come in contact with and understand filtering processes that are adaptive and learn where such devices are used in practice. For this reason, we have added Chapter 14, where Wiener and least mean square (LMS) filtering are introduced. We provide numerous examples of how these filters are used, and we expect that this will stimulate the student's interest to continuously be involved in the digital signal processing discipline.
11. We introduce the fundamentals of digital sampling and the effect it has on the spectrum.
12. At the end of each chapter we summarize the new definitions and concepts that were introduced in the chapter.
13. The material is introduced in a concise format but is elucidated by a large number of examples.
14. The book has been arranged in such a way that it can be used for a one- or two-semester course. Furthermore, the track can be analog, digital, or analog–digital.

The text consists of 14 chapters. Chapter 1 introduces both analog and digital signal presentation. It also introduces the presentation of signals by a complete set of orthogonal signals.

Chapter 2 introduces linear and time-invariant continuous-time systems. In addition, the chapter covers convolution and impulse response of such systems.

Chapter 3 introduces discrete-type systems and their solution. It also discusses how to simulate analog systems using discrete methods.

Chapter 4 presents the analysis of periodic signals in Fourier series, the amplitude and phase spectra of these signals, as well as the effect that linear time-invariant systems have on them.

Chapter 5 develops the Fourier transform and its great utility in identifying systems, studying the spectra of signals as well as the influence that systems have on these spectra, known as filtering of signals. The Gibbs' phenomenon is also introduced, along with its significance in the study of signals.

Chapter 6 introduces the sampling theorem and the importance of signal bandwidth in the aliasing problem.

Chapter 7 introduces the discrete-time Fourier transform and the discrete Fourier transform. With examples, this chapter gives a clear understanding of the effects of decreasing the sampling time and padding with zeros the sequences on the spectra of discrete signals.

Chapter 8 presents in some detail the Laplace transform and its usefulness in solving differential equations, identifying analog systems, and producing transfer functions of systems, as well as its use in feedback control of systems. The Bode plots are also introduced.

Chapter 9 presents the z-transform and its applications in solving difference equations, developing the transfer functions of discrete systems, and finding the frequency response of discrete systems.

Chapter 10 brings forth the analog filter design. Specifically, it introduces the Butterworth and Chebyshev filter, and finally, it introduces the design of analog filters with the use of MATLAB functions.

Chapter 11 introduces the digital filter, known as the finite impulse response or the nonrecursive filter.

Chapter 12 introduces the infinite impulse response digital filter and its use for filtering discrete signals.

Chapter 13 develops the fundamentals of random variables and their use for finding the spectrums of stationary processes' random sequences. This chapter introduces the Wiener–Kinthcin relation and the nonparametric spectral estimation.

Chapter 14 characterizes different types of filtering and their uses. Particularly, it introduces the use of Wiener filtering and least mean squares filtering. It presents several examples with applications to noise elimination, system identification, and channel equalization.

The following are some suggestions in using the text.

One-semester course: Analog and digital signal processing
- Chapter 1: 1.1 → 1.3
- Chapter 2: 2.1 → 2.7
- Chapter 3: 3.1 → 3.4
- Chapter 5: 5.1 → 5.3
- Chapter 6: 6.1 → 6.2
- Chapter 7: 7.5 → 7.6
- Chapter 8: 8.1 → 8.3
- Chapter 10: 10.1 → 10.5
- Chapter 11: 11.1 → 11.3

One-semester course: Analog signal processing
- Chapter 1: 1.1 → 1.3
- Chapter 2: 2.1 → 2.7
- Chapter 4: 4.1 → 4.4
- Chapter 5: 5.1 → 5.2

Chapter 6: 6.1 → 6.2
Chapter 8: 8.1 → 8.7
Chapter 10: 10.1 → 10.6

One-semester course: Discrete signal processing
Chapter 1: 1.1 → 1.3
Chapter 3: 3.1 → 3.3
Chapter 5: 5.1 → 5.2
Chapter 6
Chapter 7: 7.5 → 7.6
Chapter 11: 11.1 → 11.3
Chapter 13

Two-semester course
All the chapters could be covered, including the starred chapters and sections. Some sections may be skipped at the discretion of the instructor. The starred sections may be skipped without loss of continuity.

The author acknowledges the valuable and helpful comments of Professor Nicolaos Karayiannis of the University of Houston. The author is indebted to Dr. Haluk Ogmen, department chair, and Dr. Raymond Flumerfelt, dean of the College of Engineering, who provided an excellent academic and research environment at the University of Houston.

MATLAB® is a registered trademark of The MathWorks, Inc. For product information, please contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098 USA
Tel: 508-647-7000
Fax: 508-647-7001
E-mail: info@mathworks.com
Web: www.mathworks.com

The Author

Alexander D. Poularikas received his Ph.D. from the University of Arkansas and became professor at the University of Rhode Island. He became chairman of the Engineering Department at the University of Denver and then became chairman of the Electrical and Computer Engineering Department at the University of Alabama in Huntsville. He has published six books and has edited two. Dr. Poularikas served as editor-in-chief of the Signal Processing series (1993–1997) with Artech House and is now editor-in-chief of the Electrical Engineering and Applied Signal Processing series, as well as the Engineering and Science Primers series (1998–present) with Taylor & Francis. He was a Fulbright scholar, is a lifelong senior member of IEEE, and is a member of Tau Beta Pi, Sigma Nu, and Sigma Pi. In 1990 and 1996, he received the Outstanding Educator Award of IEEE, Huntsville Section.

Abbreviations

A/D	Analog-to-digital conversion
AM	Amplitude modulation
AR	Autoregressive
ARMA	Autoregressive moving average
cdf	Cumulative density function
dB	Decibel
DFT	Discrete Fourier transform
DSBSC	Double-sideband suppressed carrier
DTFT	Discrete-time Fourier transform
FFT	Fast Fourier transform
FIR	Finite impulse response
FM	Frequency modulation
GHz	Gigahertz
IDTFT	Inverse discrete-time Fourier transform
IFFT	Inverse fast Fourier transform
iid	Independent and identically distributed
IIR	Infinite impulse response
ILT	Inverse Laplace transform
KCL	Kirchhoff current law
KVL	Kirchhoff voltage law
LMS	Least mean squares
LT	Laplace transform
LTI	Linear time invariant
MMSE	Minimum mean square error
MSE	Mean square error
NLMS	Normalized least mean squares
PAM	Pulse amplitude modulation
pdf	Probability random function
PID	Proportional integral differential controller
ROC	Region of convergence
rv	Random variable
SFG	Signal flow graph
SSB	Single sideband
WGN	White Gaussian
WN	White noise
WSS	Wide-sense stationary

Contents

Chapter 1 Signals and their functional representation **1**
1.1 Some applications involving signals 1
1.2 Fundamental representation of simple time signals 3
Periodic discrete-time signals 6
Nonperiodic continuous signals 7
Unit step function 7
Rectangular pulse function 8
Sinc function 9
Nonperiodic special discrete signals 10
Delta function 10
Comb function 13
Arbitrary sampled function 13
1.3 Signal conditioning and manipulation 14
Modulation 14
Shifting and flipping 14
Time scaling 15
Windowing of signals 17
*1.4 Representation of signals 18
Important definitions and concepts 25
Chapter 1 Problems 26
Appendix 1.1: Elementary matrix algebra 33
Appendix 1.2: Complex numbers 36
Appendix 1.1 Problems 38
Appendix 1.2 Problems 39

Chapter 2 Linear continuous-time systems **41**
2.1 Properties of systems 41
2.2 Modeling simple continuous systems 43
Electrical elements 43
Capacitor 43
Inductor 45
Resistor 47
Mechanical translation elements 48
Ideal mass element 48
Spring 48
Damper 49

Mechanical rotational elements 50
Inertial elements 50
Spring 51
Damper 52
2.3 Solutions of first-order systems 52
Zero-input and zero-state solution 54
Standard solution techniques of differential equations 56
2.4 Evaluation of integration constants: initial conditions 63
Switching of sources 64
Conservation of charge 64
Conservation of flux linkages 64
Circuit behavior of L and C 65
General switching 65
2.5 Block diagram representation 68
2.6 Convolution and correlation of continuous-time signals 71
Matched filters 83
Correlation 84
2.7 Impulse response 86
Important definitions and concepts 96
Chapter 2 Problems 97

Chapter 3 Discrete systems 111
3.1 Discrete systems and equations 111
3.2 Digital simulation of analog systems 118
*3.3 Digital simulation of higher-order differential equations 131
3.4 Convolution of discrete-time signals 135
Important definitions and concepts 141
Chapter 3 Problems 142
Appendix 3.1: Method of variation of parameters 149
Appendix 3.2: Euler's approximation for differential equations 152

Chapter 4 Periodic continuous signals and their spectrums 157
4.1 Complex functions 157
Continuous-time signals 158
Discrete-time signals 160
4.2 Fourier series of continuous functions 161
Fourier series in complex exponential form 162
Fourier series in trigonometric form 165
4.3 Features of periodic continuous functions 169
Parseval's formula 169
Symmetric functions 170
Even function 172
Odd function 172
*Finite signals 172
*Convolution 173

4.4 Linear systems with periodic inputs ... 174
Important definitions and concepts ... 180
Chapter 4 Problems ... 181

Chapter 5 Nonperiodic signals and their Fourier transform ... 189
5.1 Direct and inverse Fourier transform ... 190
Real functions ... 194
Real and even functions ... 195
Real and odd functions ... 196
5.2 Properties of Fourier transforms ... 196
Linearity ... 196
Symmetry ... 196
Time shifting ... 199
Scaling ... 200
Central ordinate ... 200
Frequency shifting ... 202
Modulation ... 202
Derivatives ... 208
Parseval's theorem ... 213
Time convolution ... 216
Frequency convolution ... 217
Summary of continuous-time Fourier properties ... 218
*5.3 Some special Fourier transform pairs ... 220
*5.4 Effects of truncation and Gibbs' phenomenon ... 225
*5.5 Linear time-invariant filters ... 226
Distortionless filter ... 228
Ideal low-pass filter ... 229
Ideal high-pass filter ... 230
Important definitions and concepts ... 231
Chapter 5 Problems ... 231
Appendix 5.1 ... 237

Chapter 6 Sampling of continuous signals ... 239
6.1 Fundamentals of sampling ... 239
6.2 The sampling theorem ... 244
Construction of analog signal from its sampled values ... 252
Important definitions and concepts ... 253
Chapter 6 Problems ... 254

Chapter 7 Discrete-time transforms ... 257
7.1 Discrete-time Fourier transform (DTFT) ... 257
Approximating the Fourier transform ... 257
7.2 Summary of DTFT properties ... 260
7.3 DTFT of finite time sequences ... 262
Windowing ... 266

7.4 Frequency response of linear time-invariant (LTI) discrete systems....268
7.5 The discrete Fourier transform (DFT)....269
7.6 Summary of the DFT properties....271
*7.7 Multirate digital signal processing....284
Down sampling (or decimation)....284
Frequency domain of down-sampled signals....286
Interpolation (up sampling) by a factor U....291
Frequency domain characterization of up-sampled signals....292
Important definitions and concepts....295
Chapter 7 Problems....295
Appendix 7.1: Proofs of the DTFT properties....298
Appendix 7.2: Proofs of DFT properties....300
Appendix 7.3: Fast Fourier transform (FFT)....304

Chapter 8 Laplace transform....309
8.1 One-sided Laplace transform....309
8.2 Summary of the Laplace transform properties....312
8.3 Systems analysis: transfer functions of LTI systems....316
8.4 Inverse Laplace transform (ILT)....328
MATLAB function residue....329
8.5 Problem solving with Laplace transform....336
8.6 Frequency response of LTI systems....352
8.7 Pole location and the stability of LTI systems....361
Simple-order poles....361
Multiple-order poles....363
*8.8 Feedback for linear systems....365
Cascade stabilization of systems....365
Parallel composition....366
Feedback stabilization....367
Sensitivity in feedback....368
Rejection of disturbance using feedback....369
Step response....370
Proportional controllers....371
Proportional integral differential (PID) controllers....375
*8.9 Bode plots....377
Bode plots of constants....377
Bode diagram for differentiator....378
Bode diagram for an integrator....379
Bode diagram for a real pole....379
Important definitions and concepts....383
Chapter 8 Problems....383
Appendix 8.1: Proofs of Laplace transform properties....397

Chapter 9 The z-transform, difference equations, and discrete systems **401**
9.1 The z-transform 401
9.2 Convergence of the z-transform 405
9.3 Properties of the z-transform 412
Summary of z-transform properties 413
9.4 z-Transform pairs 423
9.5 Inverse z-transform 423
9.6 Transfer function 431
*Higher-order transfer functions 437
9.7 Frequency response of first-order discrete systems 438
Phase shift in discrete systems 443
*9.8 Frequency response of higher-order digital systems 443
9.9 z-Transform solution of first-order difference equations 447
*9.10 Higher-order difference equations 450
Method of undetermined coefficients 454
Important definitions and concepts 459
Chapter 9 Problems 459
*Appendix 9.1: Proofs of the z-transform properties 473

Chapter 10 Analog filter design **477**
10.1 General aspects of filters 477
10.2 Butterworth filter 479
10.3 Chebyshev low-pass filter 486
10.4 Phase characteristics 494
10.5 Frequency transformations 494
Low-pass-to-low-pass transformation 494
Low-pass-to-high-pass transformation 495
Low-pass-to-band-pass transformation 495
Low-pass-to-band-stop transformation 498
10.6 Analog filter design using MATLAB functions 500
Butterworth filter design 500
Important definitions and concepts 501
Chapter 10 Problems 501

Chapter 11 Finite Impulse Response (FIR) filters **505**
11.1 Properties of FIR filters 505
Causality 505
Frequency normalization 505
Phase consideration 506
Scaling the digital transfer function 507
Symmetric FIR low-pass filters 508
11.2 FIR filters using the Fourier series approach 509

11.3 FIR filters using windows 513
Windows 513
High-pass FIR filters 515
Band-pass FIR filters 516
Band-stop FIR filters 516
*11.4 Prescribed filter specifications using a Kaiser window 519
11.5 MATLAB FIR filter design 522
Low-pass FIR filter 522
High-pass FIR filter 522
Band-pass FIR filter 522
Band-stop FIR filter 523
Window use 523
Important definitions and concepts 523
Chapter 11 Problems 523

Chapter 12 Infinite Impulse Response (IIR) filters 525
12.1 The impulse-invariant method approximation in the time domain 525
12.2 Bilinear transformation 532
12.3 Frequency transformation for digital filters 538
Low-pass-to-low-pass transformation 538
Low-pass-to-high-pass transformation 539
Low-pass-to-band-pass transformation 540
Low-pass-to-band-pass transformation 542
12.4 Recursive versus non-recursive design 542
Important defintions and concepts 543
Chapter 12 Problems 543

Chapter 13 Random variables, sequences, and power spectra densities 545
13.1 Random signals and distributions 545
Stationary and ergodic processes 548
13.2 Averages 548
Mean value 548
Correlation 549
Covariance 553
Independent and uncorrelated rv's 553
13.3 Stationary processes 554
Autocorrelation matrix 554
Purely random process (white noise, WN) 557
Random walk (RW) 557
13.4 Special random signals and probability density functions 557
White noise 557
Gaussian processes 558
Algorithm to produce normalized Gaussian distribution 558

Lognormal distribution........559
Algorithm to produce lognormal distribution........559
Chi-square distribution........560
13.5 Wiener–Kintchin relations........560
13.6 Filtering random processes........562
Spectral factorization........565
Autoregressive process (AR)........565
13.7 Nonparametric spectra estimation........568
Periodogram........568
Correlogram........568
Computation of $\hat{S}_p(ej\omega)$ and $\hat{S}_c(ej\omega)$ using FFT........568
General remarks on the periodogram........570
Blackman–Tukey (BT) method........570
Bartlett method........572
Welch method........573
Modified Welch method........575
The Blackman–Tukey periodogram with the Bartlett window........577
Important definitions and concepts........578
Chapter 13 Problems........579

***Chapter 14 Least square system design, Wiener filter, and the LMS filter........583**
14.1 The least-squares technique........583
Linear least squares........587
14.2 The mean square error........590
The Wiener filter........591
The Wiener solution........594
Orthogonality condition........597
14.3 Wiener filtering examples........597
Minimum mean square error (MMSE)........602
Optimum filter (w^o)........603
14.4 The least mean square (LMS) algorithm........608
The LMS algorithm........609
14.5 Examples using the LMS algorithm........614
Important definitions and concepts........623
Chapter 14 Problems........623

Appendix A Mathematical formulas........627
A.1 Trigonometric identities........627
A.2 Orthigonality........629
A.3 Summation of trigonometric forms........629
A.4 Summation formulas........630
Finite summation formulas........630
Infinite summation formulas........630
A.5 Series expansions........631

A.6 Logarithms 631
A.7 Some definite integrals 632

Appendix B Suggestions and explanations for MATLAB use 633
B.1 Creating a directory 633
B.2 Help 633
B.3 Save and load 634
B.4 MATLAB as calculator 634
B.5 Variable names 634
B.6 Complex numbers 634
B.7 Array indexing 635
B.8 Extracting and inserting numbers in arrays 635
B.9 Vectorization 635
B.10 Matrices 636
B.11 Produce a periodic function 636
B.12 Script files 636
Script file pexp.m 637
B.13 Functions 637
B.14 Subplots 638
B.15 Figures 638
B.16 Changing the scales of the axes of a figure 639
B.17 Writing Greek letters 639
B.18 Subscripts and superscripts 640
B.19 Lines in plots 640

Index 641