Table of Contents

Preface ix
Acknowledgements xiii

1 Signals and Signal Processing 1

1.1 Characterization and Classification of Signals 1
1.2 Typical Signal Processing Operations 4
1.3 Examples of Typical Signals 13
1.4 Typical Signal Processing Applications 21
1.5 Why Digital Signal Processing? 37

2 Discrete-Time Signals in the Time Domain 41

2.1 Time-Domain Representation 42
2.2 Operations on Sequences 46
2.3 Operations on Finite-Length Sequences 55
2.4 Typical Sequences and Sequence Representation 62
2.5 The Sampling Process 72
2.6 Correlation of Signals 74
2.7 Random Signals 80
2.8 Summary 81
2.9 Problems 81
2.10 MATLAB Exercises 87

3 Discrete-Time Signals in the Frequency Domain 89

3.1 The Continuous-Time Fourier Transform 89
3.3 Discrete-Time Fourier Transform Theorems 105
3.4 Energy Density Spectrum of a Discrete-Time Sequence 111
3.5 Band-Limited Discrete-Time Signals 112
3.6 DTFT Computation Using MATLAB 113
3.7 The Unwrapped Phase Function 113
3.8 Digital Processing of Continuous-Time Signals 115

3.9 Sampling of Bandpass Signals 129
3.10 Effect of Sample-and-Hold Operation 131
3.11 Summary 132
3.12 Problems 133
3.13 MATLAB Exercises 142

4 Discrete-Time Systems 143

4.1 Discrete-Time System Examples 143
4.2 Classification of Discrete-Time Systems 149
4.3 Impulse and Step Responses 153
4.4 Time-Domain Characterization of LTI Discrete-Time Systems 154
4.5 Simple Interconnection Schemes 161
4.6 Finite-Dimensional LTI Discrete-Time Systems 164
4.7 Classification of LTI Discrete-Time Systems 172
4.8 Frequency-Domain Representations of LTI Discrete-Time Systems 175
4.9 Phase and Group Delays 185
4.10 Summary 189
4.11 Problems 190
4.12 MATLAB Exercises 198

5 Finite-Length Discrete Transforms 199

5.1 Orthogonal Transforms 199
5.2 The Discrete Fourier Transform 201
5.3 Relation Between the DTFT and the DFT and Their Inverses 205
5.4 Circular Convolution 211
5.5 Classifications of Finite-Length Sequences 216
5.6 DFT Symmetry Relations 221
5.7 Discrete Fourier Transform Theorems 224
5.8 Fourier-Domain Filtering 230
5.9 Computation of the DFT of Real Sequences 232
5.10 Linear Convolution Using the DFT 234
5.11 Short-Time Fourier Transform 245
5.12 Discrete Cosine Transform 249
5.13 The Haar Transform 256
5.14 Energy Compaction Properties 259
5.15 Summary 262
5.16 Problems 262

5.17 MATLAB Exercises 275

6 *z*-Transform 277

6.1 Definition 277
6.2 Rational *z*-Transforms 281
6.3 Region of Convergence of a Rational *z*-Transform 283
6.4 The Inverse *z*-Transform 289
6.5 *z*-Transform Theorems 297
6.6 Computation of the Convolution Sum of Finite-Length Sequences 305
6.7 The Transfer Function 308
6.8 Summary 320
6.9 Problems 320
6.10 MATLAB Exercises 332

7 LTI Discrete-Time Systems in the Transform Domain 333

7.1 Transfer Function Classification Based on Magnitude Characteristics 333
7.2 Transfer Function Classification Based on Phase Characteristics 342
7.3 Types of Linear-Phase FIR Transfer Functions 349
7.4 Simple Digital Filters 360
7.5 Complementary Transfer Functions 379
7.6 Inverse Systems 385
7.7 System Identification 389
7.8 Digital Two-Pairs 392
7.9 Algebraic Stability Test 394
7.10 Summary 399
7.11 Problems 400
7.12 MATLAB Exercises 414

8 Digital Filter Structures 417

8.1 Block Diagram Representation 418
8.2 Equivalent Structures 421
8.3 Basic FIR Digital Filter Structures 422
8.4 Basic IIR Digital Filter Structures 427
8.5 Realization of Basic Structures Using MATLAB 433
8.6 Allpass Filters 436
8.7 Parametrically Tunable Low-Order IIR Digital Filter Pairs 445
8.8 IIR Tapped Cascaded Lattice Structures 447

8.9 FIR Cascaded Lattice Structures 452
8.10 Parallel Allpass Realization of IIR Transfer Functions 460
8.11 Tunable High-Order Digital Filters 465
8.12 Computational Complexity of Digital Filter Structures 472
8.13 Summary 472
8.14 Problems 473
8.15 MATLAB Exercises 487

9 IIR Digital Filter Design 489

9.1 Preliminary Considerations 489
9.2 Bilinear Transformation Method of IIR Filter Design 494
9.3 Design of Lowpass IIR Digital Filters 499
9.4 Design of Highpass, Bandpass, and Bandstop IIR Digital Filters 501
9.5 Spectral Transformations of IIR Filters 505
9.6 IIR Digital Filter Design Using MATLAB 512
9.7 Computer-Aided Design of IIR Digital Filters 515
9.8 Summary 519
9.9 Problems 519
9.10 MATLAB Exercises 525

10 FIR Digital Filter Design 527

10.1 Preliminary Considerations 527
10.2 FIR Filter Design Based on Windowed Fourier Series 531
10.3 Computer-Aided Design of Equiripple Linear-Phase FIR Filters 546
10.4 Design of Minimum-Phase FIR Filters 555
10.5 FIR Digital Filter Design Using MATLAB 556
10.6 Design of Computationally Efficient FIR Digital Filters 573
10.7 Summary 586
10.8 Problems 587
10.9 MATLAB Exercises 594

11 DSP Algorithm Implementation 599

11.1 Basic Issues 599
11.2 Structure Simulation and Verification Using MATLAB 610
11.3 Computation of the Discrete Fourier Transform 617
11.4 Fast DFT Algorithms Based on Index Mapping 632
11.5 DFT and IDFT Computation Using MATLAB 640

11.6 Sliding Discrete Fourier Transform 642
11.7 DFT Computation over a Narrow Frequency Band 642
11.8 Number Representation 647
11.9 Handling of Overflow 652
11.10 Summary 653
11.11 Problems 653
11.12 MATLAB Exercises 661

12 Analysis of Finite Wordlength Effects 663

12.1 The Quantization Process and Errors 664
12.2 Quantization of Fixed-Point Numbers 665
12.3 Quantization of Floating-Point Numbers 668
12.4 Analysis of Coefficient Quantization Effects 668
12.5 A/D Conversion Noise Analysis 681
12.6 Analysis of Arithmetic Round-Off Errors 691
12.7 Dynamic Range Scaling 695
12.8 Signal-to-Noise Ratio in Low-Order IIR Filters 706
12.9 Low-Sensitivity Digital Filters 710
12.10 Reduction of Product Round-Off Noise Using Error Feedback 716
12.11 Limit Cycles in IIR Digital Filters 719
12.12 Round-Off Errors in FFT Algorithms 727
12.13 Summary 730
12.14 Problems 731
12.15 MATLAB Exercises 736

13 Multirate Digital Signal Processing Fundamentals 739

13.1 The Basic Sampling Rate Alteration Devices 740
13.2 Multirate Structures for Sampling Rate Conversion 750
13.3 Multistage Design of Decimator and Interpolator 758
13.4 The Polyphase Decomposition 760
13.5 Arbitrary-Rate Sampling Rate Converter 771
13.6 Nyquist Filters 783
13.7 CIC Decimators and Interpolators 792
13.8 Summary 796
13.9 Problems 797
13.10 Matlab Exercises 805

14 Multirate Filter Banks and Wavelets 807

14.1 Digital Filter Banks 807
14.2 Two-Channel Quadrature-Mirror Filter Bank 813
14.3 Perfect Reconstruction Two-Channel FIR Filter Banks 823
14.4 L-Channel QMF Banks 832
14.5 Multilevel Filter Banks 840
14.6 Discrete Wavelet Transform 844
14.7 Summary 853
14.8 Problems 853
14.9 MATLAB Exercises 861

A Analog Lowpass Filter Design 863

A.1 Analog Filter Specifications 863
A.2 Butterworth Approximation 865
A.3 Chebyshev Approximation 867
A.4 Elliptic Approximation 870
A.5 Linear-Phase Approximation 871
A.6 Analog Filter Design Using MATLAB 872
A.7 Analog Lowpass Filter Design Examples 875
A.8 A Comparison of the Filter Types 877
A.9 Anti-Aliasing Filter Design 880
A.10 Reconstruction Filter Design 882

B Design of Analog Highpass, Bandpass, and Bandstop Filters 887

B.1 Analog Highpass Filter Design 887
B.2 Analog Bandpass Filter Design 889
B.3 Analog Bandstop Filter Design 892

C Discrete-Time Random Signals 893

C.1 Statistical Properties of a Random Variable 893
C.2 Statistical Properties of a Random Signal 895
C.3 Wide-Sense Stationary Random Signal 896
C.4 Concept of Power in a Random Signal 897
C.5 Ergodic Signal 898
C.6 Transform-Domain Representations of Random Signals 899
C.7 White Noise 901
C.8 Discrete-Time Processing of Random Signals 901

Bibliography 907
Index 927