

Contents

PREFACE

xiii

1 INTRODUCTION

i

- 1.1 Brief Historical Introduction and Some Comments 1
- 1.2 An Overview of Digital Signal Processing 3
- 1.3 Organization of the Book 5

2 THEORY OF DISCRETE-TIME LINEAR SYSTEMS

9

- 2.1 Introduction 9
- 2.2 Sequences 9
- 2.3 Representation of Arbitrary Sequences 12
- 2.4 Linear, Time-Invariant Systems 13
- 2.5 Causality, Stability 14
- 2.6 Difference Equations 16
- 2.7 Frequency Response 20
- 2.8 Frequency Response of First-Order Systems 22
- 2.9 Frequency Response of Second-Order Systems 23
- 2.10 Discrete Fourier Series 24
- 2.11 Comments on Units of Frequency 25
- 2.12 Relation Between Continuous and Discrete Systems 26

- 2.13 The z Transform 28
- 2.14 Relation Between the z Transform and the Fourier Transform of a Sequence 30
- 2.15 The Inverse z Transform 32
- 2.16 Properties of the z Transform 33
- 2.17 Solution of Difference Equations Using the One-Sided z Transform 37
- 2.18 Geometric Evaluation of the Fourier Transform 39
- 2.19 Digital Filter Realizations (Structures) 40
- 2.20 Structures For All-Zero Filters 46
- 2.21 The Discrete Fourier Transform 50
- 2.22 Properties of the DFT 57
- 2.23 Convolution of Sequences 59
- 2.24 Linear Convolution of Finite Duration Sequences 61
- 2.25 Sectioned Convolutions 63
- 2.26 The Discrete Hilbert Transform 67
- 2.27 Hilbert-Transform Relations for Real Signals 70
- References 73

3 THE THEORY AND APPROXIMATION OF FINITE DURATION IMPULSE RESPONSE DIGITAL FILTERS

75

- 3.1 Introduction 75
- 3.2 Issues in Filter Design 75
- 3.3 Discussion of FIR Filters 76
- 3.4 Characteristics of FIR Filters with Linear Phase 77
- 3.5 Frequency Response of Linear Phase FIR Filters 81
- 3.6 Positions of the Zeros of Linear Phase FIR Filters 84
- 3.7 Design Techniques for Linear Phase FIR Filters 88
- 3.8 Design Technique No. 1—Windowing 88
- 3.9 Rectangular Window 90
- 3.10 "Generalized" Hamming Window 91
- 3.11 Kaiser Window 93
- 3.12 Examples of a Windowed Lowpass Filter 94
- 3.13 Issues with Windowing 101
- 3.14 Some Practical Techniques with Windows 102
- 3.15 Additional Examples of Window Designed Filters 103
- 3.16 Summary of Windows 105
- 3.17 Design Technique No. 2—Frequency Sampling 105
- 3.18 Solution for Optimization 108
- 3.19 Linear Programming 110
- 3.20 Types 1 and 2 112
- 3.21 Type 1 Designs—Linear Phase Constraints 113
- 3.22 Type 2 Designs—Linear Phase Constraints 115
- 3.23 Some General Results on the Design of Frequency Sampling Filters 117
- 3.24 Summary of Frequency Sampling Design 121
- 3.25 Design Technique No. 3—Optimal (Minimax Error) Filters 123

- 3.26 Weighted Chebyshev Approximation 124
- 3.27 Constraint on the Number of Extrema of the Frequency Response of a Linear Phase Filter 127
- 3.28 Nonlinear Equation Solution for Maximal Ripple FIR Filters 130
- 3.29 Polynomial Interpolation Solution for Maximal Ripple FIR Filters 132
- 3.30 Remez Exchange Algorithm Design of Optimal FIR Filters 136
- 3.31 Linear Programming Design of Optimal FIR Filters 140
- 3.32 Characteristics of Optimal Case 1 Lowpass Filters 141
- 3.33 Some Additional Properties of Case 1 Optimal Lowpass Filters 148
- 3.34 Relations Between Optimal Lowpass Filter Parameters 153
- 3.35 Properties of Case 2 Optimal Lowpass Filters 157
- 3.36 Characteristics of Optimal Differentiators 164
- 3.37 Characteristics of Optimal Hilbert Transformers 168
- 3.38 Multiple Band Optimal FIR Filters 177
- 3.39 Design of Filters with Simultaneous Constraints on the Time and Frequency Response 180
- 3.40 Direct Comparison Between FIR Lowpass Filters 183
- References 184
- Appendix 187

4 THEORY AND APPROXIMATION OF INFINITE IMPULSE RESPONSE DIGITAL FILTERS

205

- 4.1 Introduction 205
- 4.2 Some Elementary Properties of IIR Filters—Magnitude-Squared Response, Phase Response, and Group Delay 209
- 4.3 Techniques for Determining IIR Filter Coefficients 210
- 4.4 Digital Filter Design from Continuous-Time Filters 211
- 4.5 Mapping of Differentials 212
- 4.6 Impulse Invariant Transformation 216
- 4.7 Bilinear Transformation 219
- 4.8 Matched z Transformation 224
- 4.9 Review of Design Techniques for Analog Lowpass Filters 226
- 4.10 Design Charts for Lowpass Filters 238
- 4.11 Comparisons Between Impulse Invariant and Bilinear Transformation for Elliptic Filters 252
- 4.12 Frequency Transformations 257
- 4.13 Direct Design of Digital Filters 263
- 4.14 Optimization Methods for Designing IIR Filters 267
- 4.15 Summary of IIR Filter Design Techniques 282
- 4.16 Some Comparisons Between FIR and IIR Filters 284
- 4.17 Comparisons of Optimum FIR Filters and Delay Equalized Elliptic Filters 286
- References 293

5 FINITE WORD LENGTH EFFECTS IN DIGITAL FILTERS

- 5.1 Introduction 295
- 5.2 Analog-to-Digital Conversion 296
- 5.3 Digital-to-Analog Conversion 300
- 5.4 Types of Arithmetic in Digital Systems 302
- 5.5 Fixed Point Arithmetic 302
- 5.6 Floating Point Arithmetic 303
- 5.7 Block Floating Point 305
- 5.8 Types of Quantization in Digital Filters 306
- 5.9 Truncation 307
- 5.10 Rounding 308
- 5.11 Roundoff Noise in Recursive Structures—Fixed Point Arithmetic 309
- 5.12 Dynamic Range Constraints—Fixed Point Case 315
- 5.13 Dynamic Range Constraints in Direct Form Realizations 320
- 5.14 Dynamic Range Considerations in Parallel Form Realizations 321
- 5.15 Dynamic Range Considerations in Cascade Form Realizations 323
- 5.16 Ordering and Pairing in Cascade Realizations 323
- 5.17 Summary of Roundoff Noise—Dynamic Range Interaction 325
- 5.18 Additional Comments on Dynamic Range—Roundoff Noise Interactions 326
- 5.19 Roundoff Noise in Nonrecursive Structures—Fixed Point Analysis 328
- 5.20 Roundoff Noise in Direct Form Nonrecursive Realizations 328
- 5.21 Roundoff Noise in Cascade Form Nonrecursive Realizations 331
- 5.22 Roundoff Noise—Floating Point Realizations of Recursive Structures 334
- 5.23 Coefficient Quantization 336
- 5.24 Coefficient Quantization in Recursive Structures 337
- 5.25 Coefficient Quantization in the Direct Form Realization 337
- 5.26 Experimental Verification of Coefficient Quantization Model 340
- 5.27 Optimization of Quantized Coefficients 341
- 5.28 Coefficient Quantization in the Implementation of a Pole-Pair 344
- 5.29 Coefficient Quantization in Nonrecursive Structures 345
- 5.30 Coefficient Quantization in Direct Form Realizations of FIR Filters 346
- 5.31 Coefficient Quantization in Cascade Realizations of FIR Filters 349
- 5.32 Limit Cycle Oscillations 350
- References 353

6 SPECTRUM ANALYSIS AND THE FAST FOURIER TRANSFORM

356

- 6.1 Introduction 356
- 6.2 Introduction to Radix-2 FFT's 357
- 6.3 Some Properties of Radix 2 Decimation-in-Time FFT 361
- 6.4 Data Shuffling and Bit Reversal 363
- 6.5 FFT FORTRAN Program 366
- 6.6 Decimation-in-Frequency Algorithm 368
- 6.7 Computing an Inverse DFT by Doing a Direct DFT 371
- 6.8 A Unified Approach to the FFT 371
- 6.9 Radix 2 Algorithms 379
- 6.10 Spectrum Analysis at a Single Point in the z Plane 381
- 6.11 Spectrum Analysis Using the FFT 383
- 6.12 Some Considerations in Spectrum Analysis 384
- 6.13 Relation of "Hopping" FFT's to Filter Banks 386
- 6.14 Windows in Spectrum Analysis 388
- 6.15 Measurement of the Spectrum over a Limited Angle in the z Plane by the FFT 390
- 6.16 Bluestein's Algorithm 392
- 6.17 The Chirp z Transform Algorithm 393
- 6.18 Power Spectrum for Noisy Signals 399
- 6.19 Convolution and Correlation Using Number Theoretic Transforms 419
- References 433
- Appendix 435

7 AN INTRODUCTION TO THE THEORY OF TWO-DIMENSIONAL SIGNAL PROCESSING

438

- 7.1 Introduction 438
- 7.2 Two-Dimensional Signals 438
- 7.3 Two-Dimensional Systems 440
- 7.4 Causality, Separability, Stability 441
- 7.5 Two-Dimensional Difference Equations 442
- 7.6 Frequency Domain Techniques 444
- 7.7 Two-Dimensional z Transforms 446
- 7.8 Finite Sequences 447
- 7.9 Convolution Property of z Transforms 447
- 7.10 Two-Dimensional DFT 448
- 7.11 Filter Design Considerations 450
- 7.12 IIR Filters 451
- 7.13 Stability Considerations 451
- 7.14 FIR Filters 455
- 7.15 Two-Dimensional Windows 456
- 7.16 Example of Window Design of a Lowpass Filter 457
- 7.17 Frequency Sampling Filters 461
- 7.18 Two-Dimensional Frequency Sampling Lowpass Filters 468
- 7.19 Optimal (Minimax Error) Two-Dimensional Filter Design 470
- 7.20 Frequency Transformations From One to Two Dimensions 472
- 7.21 Some Examples of Picture Processing 478
- References 482

8 INTRODUCTION TO DIGITAL HARDWARE

484

- 8.1 Introduction 484
- 8.2 Discussion of Design Procedures for Digital Signal Processing Hardware 485
- 8.3 Boolean Nomenclature; Examples of Simple Logic Nets 491
- 8.4 The Major Logic Families 495
- 8.5 Commercial Logic Packages: Gates, Multiplexers, and Decoders; Flip-Flops; Arithmetic Units; Memories 504
- 8.6 Multipliers 514
- 8.7 Dividers and Floating Point Hardware 524
- 8.8 An Illustrative Example; Design of a Fast Array Multiplier 533
- 8.9 Summary 536
- References 540

9 SPECIAL-PURPOSE HARDWARE FOR DIGITAL FILTERING AND SIGNAL GENERATION

541

- 9.1 Introduction 541
- 9.2 Direct Form FIR Hardware 542
- 9.3 Parallelism for Direct Form FIR 544
- 9.4 Cascade FIR Filter 546
- 9.5 Highly Parallel FIR Direct Form 549
- 9.6 Direct Form IIR Filters 551
- 9.7 Cascade Form IIR Filters 553
- 9.8 Multiplexing 553
- 9.9 Digital Touch-Tone Receiver (TTR) 557
- 9.10 Digital Time Division Multiplexing (TDM) to Frequency Division Multiplexing (FDM) Translator 559
- 9.11 Partitioning of Digital Filters for IC Realization 562
- 9.12 Hardware Realization of a Digital Frequency Synthesizer 563
- 9.13 Techniques for Generating Pseudo-Random Numbers 565
- 9.14 Techniques for Generating Gaussian Random Numbers 570
- References 571

10 SPECIAL-PURPOSE HARDWARE FOR THE FFT

573

- 10.1 Introduction 573
- 10.2 Review of FFT Fundamentals 573
- 10.3 FFT Indexing—Bit Reversal and Digit Reversal for Fixed Radices 579
- 10.4 Comparison of Computations for Radices 2, 4, and 8 585
- 10.5 Introduction to Quantization Effects in FFT Algorithms 587

- 10.6 Some Hardware Considerations for Radix 2 Algorithms 594
- 10.7 An "Optimum" Radix 2 Hardware Structure 597
- 10.8 Discussion of Parallel Processing to Speed Up FFT 598
- 10.9 FFT Computation Using Fast Scratch Memory 599
- 10.10 Radix 2 and Radix 4 Parallel Structures Using RAM's 600
- 10.11 General Discussion of the Pipeline FFT 602
- 10.12 Radix 2 Pipeline FFT 604
- 10.13 Radix 4 Pipeline FFT 609
- 10.14 Comparison of Radix 2 and Radix 4 Pipeline FFT's 613
- 10.15 Discussion of More Highly Parallel FFT Hardware Structures 614
- 10.16 Overall Design Philosophy for Special FFT Processors 619
- 10.17 Overlapped FFT with Random Access Memory 620
- 10.18 Real-Time Convolution via FFT Using a Single RAM and One AE 620
- 10.19 10-MHz Pipeline Convolver 623
- References 626

11 GENERAL-PURPOSE HARDWARE FOR SIGNAL PROCESSING FACILITIES

627

- 11.1 Introduction 627
- 11.2 Special- and General-Purpose Computers 628
- 11.3 How to Describe a Computer 629
- 11.4 Running Sum Program 630
- 11.5 Input-Output Problems for Real-Time Processing 632
- 11.6 Methods of Increasing Computer Speed 634
- 11.7 Cache Memories 635
- 11.8 Arithmetic Parallelism 636
- 11.9 Parallel Operation of Memories, Arithmetic, Control, and Instruction Fetches 639
- 11.10 The Lincoln Laboratory Fast Digital Processor (FDP) 639
- 11.11 Structure of the AE's 641
- 11.12 Timing 643
- 11.13 Summary of FDP Speedup Features 644
- 11.14 Doing the FFT in the FDP 647
- 11.15 Floating Point Routines 648
- 11.16 Summary of Special Features on the FDP Caused by the Parallelism 650
- 11.17 The LSP2 (Lincoln Signal Processor 2) 652
- 11.18 A Laboratory Computer Facility for Digital Signal Processing 655
- References 657

12 APPLICATIONS OF DIGITAL SIGNAL PROCESSING TO SPEECH

658

- 12.1 Introduction 658
- 12.2 Model of Speech Production 658
- 12.3 Short-Time Spectrum Analysis 664
- 12.4 Speech Analysis-Synthesis System Based on Short-Time Spectrum Analysis 667
- 12.5 Analysis Considerations 669
- 12.6 Overall System 673
- 12.7 Channel Vocoder 675
- 12.8 Vocoder Analyzers—Signal Processing Considerations 676
- 12.9 Vocoder Synthesizers—Signal Processing Considerations 678
- 12.10 Other Vocoder Configurations 681
- 12.11 Pitch Detection and Voiced-Unvoiced Decisions 681
- 12.12 Voiced-Unvoiced (Buzz-Hiss) Detection 687
- 12.13 Homomorphic Processing of Speech 687
- 12.14 Homomorphic Vocoder 691
- 12.15 Formant Synthesis 691
- 12.16 Voiced Fricative Excitation Network 696
- 12.17 Random Number Generator 698
- 12.18 Principles of Digital Operation 699
- 12.19 Linear Prediction of Speech 700
- 12.20 A Computer Voice Response System 703
- 12.21 Summary 707
- References 707

13 APPLICATIONS TO RADAR

709

- 13.1 Introductory Discussion of Radar Principles and Applications 709
- 13.2 Radar System and Parameter Considerations 711
- 13.3 Signal Design and Ambiguity Functions 715
- 13.4 Digital Matched Filters for Radar Signals 724
- 13.5 Airborne Surveillance Radar for Air Traffic Control—Doppler Processing to Combat Clutter Problems 733
- 13.6 Long-Range Demonstration Radar (LRDR) 741
- 13.7 Digital Matched Filter for a High Performance Radar 748
- 13.8 Summary 752
- References 752

INDEX

755