
CONTENTS

| | |
|--|-----------|
| Preface to the Second Edition | xvii |
| Preface to the First Edition | xxi |
| Introduction | xxv |
| 1 Elementary Analysis | 1 |
| 1.1 Introduction | 1 |
| 1.2 Types of Discrete-Time Signals | 1 |
| 1.3 The Digital Filter as a System | 2 |
| 1.4 Characterization of Digital Filters | 8 |
| 1.5 Digital-Filter Networks | 9 |
| 1.6 Introduction to Time-Domain Analysis | 15 |
| 1.7 Convolution Summation | 21 |
| 1.8 Stability | 25 |
| 1.9 State-Space Analysis | 26 |
| References | 31 |
| Problems | 31 |
| 2 The z Transform | 43 |
| 2.1 Introduction | 43 |
| 2.2 Review of Complex Analysis | 44 |
| 2.3 Definition of z Transform | 47 |
| 2.4 z -Transform Theorems | 48 |
| 2.5 Inverse z Transform | 53 |
| 2.6 Complex Convolution | 59 |
| References | 62 |
| Problems | 62 |
| 3 The Application of the z Transform | 66 |
| 3.1 Introduction | 66 |
| 3.2 The Discrete-Time Transfer Function | 67 |
| 3.3 Stability | 69 |
| | xi |

| | | |
|----------|--|------------|
| 3.4 | Time-Domain Analysis | 78 |
| 3.5 | Frequency-Domain Analysis | 80 |
| 3.6 | Amplitude and Delay Distortion | 85 |
| 3.7 | Introduction to the Design Process | 87 |
| | References | 89 |
| | Problems | 89 |
| 4 | Realization | 97 |
| 4.1 | Introduction | 97 |
| 4.2 | Direct Realization | 98 |
| 4.3 | Direct Canonic Realization | 102 |
| 4.4 | State-Space Realization | 104 |
| 4.5 | Ladder Realization | 104 |
| 4.6 | Lattice Realization | 109 |
| 4.7 | Cascade Realization | 113 |
| 4.8 | Parallel Realization | 114 |
| 4.9 | Implementation | 115 |
| 4.10 | Topological Properties | 119 |
| | References | 129 |
| | Additional References | 129 |
| | Problems | 130 |
| 5 | Analog-Filter Approximations | 138 |
| 5.1 | Introduction | 138 |
| 5.2 | Basic Concepts | 139 |
| 5.3 | Butterworth Approximation | 143 |
| 5.4 | Chebyshev Approximation | 146 |
| 5.5 | Elliptic Approximation | 153 |
| 5.6 | Bessel Approximation | 168 |
| 5.7 | Transformations | 169 |
| | References | 172 |
| | Problems | 172 |
| 6 | Continuous-Time, Sampled, and Discrete-Time Signals | 177 |
| 6.1 | Introduction | 177 |
| 6.2 | The Fourier Transform | 177 |
| 6.3 | Generalized Functions | 182 |
| 6.4 | Fourier Series | 197 |
| 6.5 | Poisson's Summation Formula | 198 |
| 6.6 | Sampled Signals | 199 |
| 6.7 | The Sampling Theorem | 203 |
| 6.8 | Interrelations | 205 |
| 6.9 | The Processing of Continuous-Time Signals | 207 |
| | References | 213 |
| | Problems | 215 |
| 7 | Approximations for Recursive Filters | 220 |
| 7.1 | Introduction | 220 |
| 7.2 | Realizability Constraints | 221 |
| 7.3 | Invariant-Impulse-Response Method | 221 |

| | | |
|-----------|---|------------|
| 7.4 | Modified Invariant-Impulse-Response Method | 224 |
| 7.5 | Matched-z-Transformation Method | 228 |
| 7.6 | Bilinear-Transformation Method | 231 |
| 7.7 | Digital-Filter Transformations | 238 |
| | References | 244 |
| | Problems | 244 |
| 8 | Recursive Filters Satisfying Prescribed Specifications | 249 |
| 8.1 | Introduction | 249 |
| 8.2 | Design Procedure | 250 |
| 8.3 | Design Formulas | 251 |
| 8.4 | Design Using the Formulas and Tables | 262 |
| 8.5 | Constant Group Delay | 267 |
| 8.6 | Amplitude Equalization | 270 |
| | Reference | 271 |
| | Problems | 271 |
| 9 | Design of Nonrecursive Filters | 274 |
| 9.1 | Introduction | 274 |
| 9.2 | Properties of Nonrecursive Filters | 275 |
| 9.3 | Design Using the Fourier Series | 280 |
| 9.4 | Use of Window Functions | 282 |
| 9.5 | Design Based on Numerical-Analysis Formulas | 301 |
| 9.6 | Comparison between Recursive and Nonrecursive Designs | 305 |
| | References | 306 |
| | Additional References | 306 |
| | Problems | 306 |
| 10 | Random Signals | 310 |
| 10.1 | Introduction | 310 |
| 10.2 | Random Variables | 310 |
| 10.3 | Random Processes | 314 |
| 10.4 | First- and Second-Order Statistics | 316 |
| 10.5 | Moments and Autocorrelation | 318 |
| 10.6 | Stationary Processes | 319 |
| 10.7 | Frequency-Domain Representation | 319 |
| 10.8 | Discrete-Time Random Processes | 323 |
| 10.9 | Filtering of Discrete-Time Random Signals | 325 |
| | References | 327 |
| | Problems | 327 |
| 11 | Effects of Finite Word Length in Digital Filters | 330 |
| 11.1 | Introduction | 330 |
| 11.2 | Number Representation | 331 |
| 11.3 | Coefficient Quantization | 339 |
| 11.4 | Low-Sensitivity Structures | 344 |
| 11.5 | Product Quantization | 350 |
| 11.6 | Signal Scaling | 352 |
| 11.7 | Minimization of Output Roundoff Noise | 360 |
| 11.8 | Application of Error-Spectrum Shaping | 364 |

| | | |
|-----------|---|------------|
| 11.9 | Limit-Cycle Oscillations | 367 |
| | References | 380 |
| | Additional References | 382 |
| | Problems | 383 |
| 12 | Wave Digital Filters | 388 |
| 12.1 | Introduction | 388 |
| 12.2 | Sensitivity Considerations | 389 |
| 12.3 | Wave Network Characterization | 390 |
| 12.4 | Element Realizations | 391 |
| 12.5 | Lattice Wave Digital Filters | 405 |
| 12.6 | Ladder Wave Digital Filters | 412 |
| 12.7 | Filters Satisfying Prescribed Specifications | 416 |
| 12.8 | Frequency-Domain Analysis | 419 |
| 12.9 | Scaling | 422 |
| 12.10 | Elimination of Limit-Cycle Oscillations | 423 |
| 12.11 | Related Synthesis Methods | 425 |
| 12.12 | A Cascade Synthesis Based on the Wave Characterization | 426 |
| 12.13 | Choice of Structure | 434 |
| | References | 436 |
| | Additional References | 437 |
| | Problems | 438 |
| 13 | The Discrete Fourier Transform | 444 |
| 13.1 | Introduction | 444 |
| 13.2 | Definition | 444 |
| 13.3 | Inverse DFT | 446 |
| 13.4 | Properties | 446 |
| 13.5 | Interrelation between the DFT and the z Transform | 449 |
| 13.6 | Interrelation between the DFT and the CFT | 454 |
| 13.7 | Interrelation between the DFT and the Fourier Series | 456 |
| 13.8 | Nonrecursive Approximations through the Use of the DFT | 458 |
| 13.9 | Simplified Notation | 462 |
| 13.10 | Periodic Convolutions | 463 |
| 13.11 | Fast-Fourier-Transform Algorithms | 465 |
| 13.12 | Digital-Filter Implementation | 477 |
| | References | 482 |
| | Additional References | 483 |
| | Problems | 483 |
| 14 | Design of Recursive Filters Using Optimization Methods | 489 |
| 14.1 | Introduction | 489 |
| 14.2 | Problem Formulation | 490 |
| 14.3 | Newton's Method | 492 |
| 14.4 | Quasi-Newton Algorithms | 496 |
| 14.5 | Minimax Algorithms | 509 |
| 14.6 | Improved Minimax Algorithms | 513 |
| 14.7 | Design of Recursive Filters | 517 |

| | | |
|-----------|--|------------|
| 14.8 | Design of Recursive Delay Equalizers | 521 |
| | References | 535 |
| | Additional References | 538 |
| | Problems | 538 |
| 15 | Design of Nonrecursive Filters Using Optimization Methods | 544 |
| 15.1 | Introduction | 544 |
| 15.2 | Problem Formulation | 545 |
| 15.3 | Remez Exchange Algorithm | 549 |
| 15.4 | Improved Search Methods | 554 |
| 15.5 | Efficient Remez Exchange Algorithm | 562 |
| 15.6 | Gradient Information | 566 |
| 15.7 | Prescribed Specifications | 571 |
| 15.8 | Generalization | 574 |
| 15.9 | Digital Differentiators | 578 |
| 15.10 | Arbitrary Amplitude Responses | 583 |
| 15.11 | Multiband Filters | 583 |
| | References | 587 |
| | Additional References | 587 |
| | Problems | 588 |
| 16 | Digital Signal Processing Applications | 592 |
| 16.1 | Introduction | 592 |
| 16.2 | Sampling-Frequency Conversion | 593 |
| 16.3 | Quadrature-Mirror-Filter Banks | 602 |
| 16.4 | Hilbert Transformers | 613 |
| 16.5 | Adaptive Digital Filters | 625 |
| 16.6 | Two-Dimensional Digital Filters | 637 |
| | References | 644 |
| | Additional References | 646 |
| | Problems | 646 |
| | Appendix A Elliptic Functions | 653 |
| A.1 | Introduction | 653 |
| A.2 | Elliptic Integral of the First Kind | 653 |
| A.3 | Elliptic Functions | 656 |
| A.4 | Imaginary Argument | 656 |
| A.5 | Formulas | 659 |
| A.6 | Periodicity | 660 |
| A.7 | Transformation | 662 |
| A.8 | Series Representation | 663 |
| | References | 665 |
| | Index | 667 |