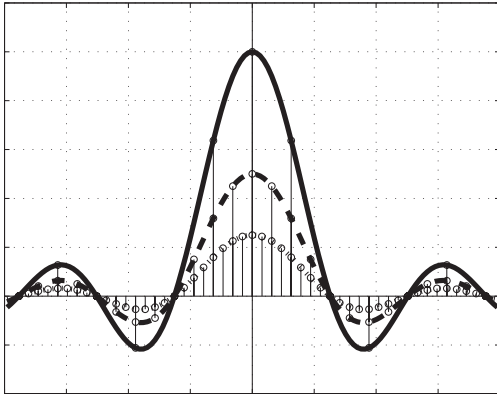

Digital Signal Processing

SIGNALS
SYSTEMS
AND FILTERS



Andreas Antoniou

University of Victoria

British Columbia

Canada

McGraw-Hill

New York Chicago San Francisco Lisbon London

Madrid Mexico City Milan New Delhi San Juan

Seoul Singapore Sydney Toronto

Chapter 1 Introduction to Digital Signal Processing

- 1.1 Introduction
- 1.2 Signals
- 1.3 Frequency-Domain Representation
- 1.4 Notation
- 1.5 Signal Processing
- 1.6 Analog Filters
- 1.7 Applications of Analog Filters
- 1.8 Digital Filters
- 1.9 Two DSP Applications
 - 1.9.1 Processing of EKG Signals
 - 1.9.2 Processing of Stock Exchange Data
- 1.10 References

Chapter 2 The Fourier Series and Fourier Transform

- 2.1 Introduction
- 2.2 Fourier Series
 - 2.2.1 Definition
 - 2.2.2 Particular Forms
 - 2.2.3 Theorems and Properties
- 2.3 Fourier Transform
 - 2.3.1 Derivation
 - 2.3.2 Particular Forms
 - 2.3.3 Theorems and Properties
- 2.4 References
- 2.5 Problems

Chapter 3 The z Transform

- 3.1 Introduction
- 3.2 Definition of z Transform

- 3.3 Convergence Properties
- 3.4 The z Transform as a Laurent Series
- 3.5 Inverse z Transform
- 3.6 Theorems and Properties
- 3.7 Elementary Discrete-Time Signals
- 3.8 z -Transform Inversion Techniques
 - 3.8.1 Use of Binomial Series
 - 3.8.2 Use of Convolution Theorem
 - 3.8.3 Use of Long Division
 - 3.8.4 Use of Initial Value Theorem
 - 3.8.5 Use of Partial Fractions
- 3.9 Spectral Representation of Discrete-Time Signals
 - 3.9.1 Frequency Spectrum
 - 3.9.2 Periodicity of Frequency Spectrum
 - 3.9.3 Interrelations
- 3.10 References
- 3.11 Problems

Chapter 4 Discrete-Time Systems

- 4.1 Introduction
- 4.2 Basic System Properties
 - 4.2.1 Linearity
 - 4.2.2 Time Invariance
 - 4.2.3 Causality
- 4.3 Characterization of Discrete-Time Systems
 - 4.3.1 Nonrecursive Systems
 - 4.3.2 Recursive Systems
- 4.4 Discrete-Time System Networks
 - 4.4.1 Network Analysis
 - 4.4.2 Implementation of Discrete-Time Systems

4.4.3 Signal Flow-Graph Analysis

4.5 Introduction to Time-Domain Analysis

4.6 Convolution Summation

4.6.1 Graphical Interpretation

4.6.2 Alternative Classification

4.7 Stability

4.8 State-Space Representation

4.8.1 Computability

4.8.2 Characterization

4.8.3 Time-Domain Analysis

4.8.4 Applications of State-Space Methods

4.9 References

4.10 Problems

Chapter 5 Application of the z Transform

5.1 Introduction

5.2 The Discrete-Time Transfer Function

5.2.1 Derivation of $H(z)$ from Difference Equation

5.2.2 Derivation of $H(z)$ from System Network

5.2.3 Derivation of $H(z)$ from State-Space Characterization

5.3 Stability

5.3.1 Constraint on Poles

5.3.2 Constraint on Eigenvalues

5.3.3 Stability Criteria

5.3.4 Test for Common Factors

5.3.5 Schur-Cohn Stability Criterion

5.3.6 Schur-Cohn-Fujiwara Stability Criterion

5.3.7 Jury-Marden Stability Criterion

5.3.8 Lyapunov Stability Criterion

5.4 Time-Domain Analysis

5.5 Frequency-Domain Analysis

- 5.5.1 Steady-State Sinusoidal Response
- 5.5.2 Evaluation of Frequency Response
- 5.5.3 Periodicity of Frequency Response
- 5.5.4 Aliasing
- 5.5.5 Frequency Response of Digital Filters

5.6 Transfer Functions for Digital Filters

- 5.6.1 First-Order Transfer Functions
- 5.6.2 Second-Order Transfer Functions
- 5.6.3 Higher-Order Transfer Functions

5.7 Amplitude and Delay Distortion

5.8 References

5.9 Problems

Chapter 6 The Sampling Process

6.1 Introduction

6.2 Fourier Transform Revisited

- 6.2.1 Impulse Functions
- 6.2.2 Periodic Signals
- 6.2.3 Unit-Step Function
- 6.2.4 Generalized Functions

6.3 Interrelation between the Fourier Series and the Fourier Transform

6.4 Poisson's Summation Formula

6.5 Impulse-Modulated Signals

- 6.5.1 Interrelation between the Fourier and z Transforms
- 6.5.2 Spectral Relationship between Discrete- and Continuous-Time Signals

6.6 The Sampling Theorem

6.7 Aliasing

6.8 Graphical Representation of Interrelations

6.9 Processing of Continuous-Time Signals Using Digital Filters

6.10 Practical A/D and D/A Converters

6.11 References

6.12 Problems

Chapter 7 The Discrete Fourier Transform

7.1 Introduction

7.2 Definition

7.3 Inverse DFT

7.4 Properties

7.4.1 Linearity

7.4.2 Periodicity

7.4.3 Symmetry

7.5 Interrelation between the DFT and the z Transform

7.5.1 Frequency-Domain Sampling Theorem

7.5.2 Time-Domain Aliasing

7.6 Interrelation between the DFT and the CFT Interrelation

7.6.1 Time-Domain Aliasing

7.7 Interrelation between the DFT and the Fourier Series

7.8 Window Technique

7.8.1 Continuous-Time Windows

7.8.2 Discrete-Time Windows

7.8.3 Periodic Discrete-Time Windows

7.8.4 Application of Window Technique

7.9 Simplified Notation

7.10 Periodic Convolutions

7.10.1 Time-Domain Periodic Convolution

7.10.2 Frequency-Domain Periodic Convolution

7.11 Fast Fourier-Transform Algorithms

7.11.1 Decimation-in-Time Algorithm

7.11.2 Decimation-in-Frequency Algorithm

7.11.3 Inverse DFT

7.12 Application of the FFT Approach to Signal Processing

7.12.1 Overlap-and-Add Method

7.12.2 Overlap-and-Save Method

7.13 References

7.14 Problems

Chapter 8 Realization of Digital Filters

8.1 Introduction

8.2 Realization

8.2.1 Direct Realization

8.2.2 Direct Canonic Realization

8.2.3 State-Space Realization

8.2.4 Lattice Realization

8.2.5 Cascade Realization

8.2.6 Parallel Realization

8.2.7 Transposition

8.3 Implementation

8.3.1 Design Considerations

8.3.2 Systolic Implementations

8.4 References

8.5 Problems

Chapter 9 Design of Nonrecursive (FIR) Filters

9.1 Introduction

9.2 Properties of Constant-Delay Nonrecursive Filters

9.2.1 Impulse Response Symmetries

9.2.2 Frequency Response

9.2.3 Location of Zeros

9.3 Design Using the Fourier Series

9.4 Use of Window Functions

9.4.1 Rectangular Window

9.4.2 Von Hann and Hamming Windows

9.4.3 Blackman Window

9.4.4 Dolph-Chebyshev Window

9.4.5 Kaiser Windows

9.4.6 Prescribed Filter Specifications

9.4.7 Other Windows

9.5 Design Based on Numerical-Analysis Formulas

9.6 References

9.7 Problems

Chapter 10 Approximations for Analog Filter

10.1 Introduction

10.2 Basic Concepts

10.2.1 Characterization

10.2.2 Laplace Transform

10.2.3 The Transfer Function

10.2.4 Time-Domain Response

10.2.5 Frequency-Domain Analysis

10.2.6 Ideal and Practical Filters

10.2.7 Realization Constraints

10.3 Butterworth Approximation

10.3.1 Derivation

10.3.2 Normalized Transfer Function

10.3.3 Minimum Filter Order

10.4 Chebyshev Approximation

10.4.1 Derivation

10.4.2 Zeros of Loss Function

10.4.3 Normalized Transfer Function

10.4.4 Minimum Order

10.5 Inverse-Chebyshev Approximation

10.5.1 Normalized Transfer Function

10.5.2 Minimum Filter Order

10.6 Elliptic Approximation

10.6.1 Fifth-Order Approximation

10.6.2 N th-Order Approximation

10.6.3 Zeros and Poles of $L(-s^2)$

10.6.4 N th-Order Approximation (n Even)

10.6.5 Specification Constraint

10.6.6 Normalized Transfer Function

10.7 Bessel-Thomson Approximation

10.8 Transformations

10.8.1 Lowpass-to-Lowpass Transformation

10.8.2 Lowpass-to-Bandpass Transformation

10.9 References

10.10 Problems

Chapter 11 Design of Recursive (IIR) Filters

11.1 Introduction

11.2 Realizability Constraints

11.3 Invariant Impulse-Response Method

11.4 Modified Invariant Impulse-Response Method

11.5 Matched- z -Transformation Method

11.6 Bilinear-Transformation Method

11.6.1 Derivation

11.6.2 Mapping Properties of Bilinear Transformation

11.6.3 The Warping Effect

11.7 Digital-Filter Transformations

11.7.1 General Transformation

11.7.2 Lowpass-to-Lowpass Transformation

11.7.3 Lowpass-to-Bandstop Transformation

11.7.4 Application

11.8 Comparison between Recursive and Nonrecursive Designs

11.9 References

11.10 Problems

Chapter 12 Recursive (IIR) Filters Satisfying Prescribed Specifications

12.1 Introduction

12.2 Design Procedure

12.3 Design Formulas

12.3.1 Lowpass and Highpass Filters

12.3.2 Bandpass and Bandstop Filters

12.3.3 Butterworth Filters

12.3.4 Chebyshev Filters

12.3.5 Inverse-Chebyshev Filters

12.3.6 Elliptic Filters

12.4 Design Using the Formulas and Tables

12.5 Constant Group Delay

12.5.1 Delay Equalization

12.5.2 Zero-Phase Filters

12.6 Amplitude-Response Equalization

12.7 References

12.8 Problems

Chapter 13 Random Signals

13.1 Introduction

13.2 Random Variables

13.2.1 Probability-Distribution Function

13.2.2 Probability-Density Function

13.2.3 Uniform Probability Density

13.2.4 Gaussian Probability Density

13.2.5 Joint Distribution

13.2.6 Mean Values and Moments

13.3 Random Processes

13.3.1 Notation

13.4 First- and Second-Order Statistics

13.5 Moments and Autocorrelation

13.6 Stationary Processes

13.7 Frequency-Domain Representation

13.8 Discrete-Time Random Processes

13.9 Filtering of Discrete-Time Random Signals

13.10 References

13.11 Problems

Chapter 14 Effects of Finite Word length in Digital Filters

14.1 Introduction

14.2 Number Representation

14.2.1 Binary System

14.2.2 Fixed-Point Arithmetic

14.2.3 Floating-Point Arithmetic

14.2.4 Number Quantization

14.3 Coefficient Quantization

14.4 Low-Sensitivity Structures

14.5 Product Quantization

14.6 Signal Scaling

14.6.1 Method A

14.6.2 Method B

14.6.3 Types of Scaling

14.6.4 Application of Scaling

14.7 Minimization of Output Roundoff Noise

14.8 Application of Error-Spectrum Shaping

14.9 Limit-Cycle Oscillations

14.9.1 Quantization Limit Cycles

- 14.9.2 Overflow Limit Cycles
- 14.9.3 Elimination of Quantization Limit Cycles
- 14.9.4 Elimination of Overflow Limit Cycles

14.10 References

14.11 Problems

Chapter 15 Design of Nonrecursive Filters Using Optimization Methods

15.1 Introduction

15.2 Problem Formulation

- 15.2.1 Lowpass and Highpass Filters
- 15.2.2 Bandpass and Bandstop Filters
- 15.2.3 Alternation Theorem

15.3 Remez Exchange Algorithm

- 15.3.1 Initialization of Extremals
- 15.3.2 Location of Maxima of the Error Function
- 15.3.3 Computation of $|E(\omega)|$ and $P_c(\omega)$
- 15.3.4 Rejection of Superfluous Potential Extremals
- 15.3.5 Computation of Impulse Response

15.4 Improved Search Methods

- 15.4.1 Selective Step-by-Step Search
- 15.4.2 Cubic Interpolation
- 15.4.3 Quadratic Interpolation
- 15.4.4 Improved Formulation

15.5 Efficient Remez Exchange Algorithm

15.6 Gradient Information

15.7 Prescribed Specifications

15.8 Generalization

- 15.8.1 Antisymmetrical Impulse Response and Odd Filter Length
- 15.8.2 Even Filter Length

15.9 Digital Differentiators

- 15.9.1 Problem Formulation
- 15.9.2 First Derivative
- 15.9.3 Prescribed Specifications

15.10 Arbitrary Amplitude Responses

15.11 Multiband Filters

15.12 References

15.13 Additional References

15.14 Problems

Chapter 16 Design of Recursive Filters Using Optimization Methods

16.1 Introduction

16.2 Problem Formulation

16.3 Newton's Method

16.4 Quasi-Newton Algorithms

16.4.1 Basic Quasi-Newton Algorithm

16.4.2 Updating Formulas for S_{k+1}

16.4.3 Inexact Line Searches

16.4.4 Practical Quasi-Newton Algorithm

16.5 Minimax Algorithms

16.6 Improved Minimax Algorithms

16.7 Design of Recursive Filters

16.7.1 Objective Function

16.7.2 Gradient Information

16.7.3 Stability

16.7.4 Minimum Filter Order

16.7.5 Use of Weighting

16.8 Design of Recursive Delay Equalizers

16.9 References

16.10 Additional References

16.11 Problems

Chapter 17 Wave Digital Filters

17.1 Introduction

17.2 Sensitivity Considerations

17.3 Wave Network Characterization

17.4 Element Realizations

17.4.1 Impedances

17.4.2 Voltage Sources

17.4.3 Series Wire Interconnection

17.4.4 Parallel Wire Interconnection

17.4.5 2-Port Adaptors

17.4.6 Transformers

17.4.7 Unit Elements

17.4.8 Circulators

17.4.9 Resonant Circuits

17.4.10 Realizability Constraint

17.5 Lattice Wave Digital Filters

17.5.1 Analysis

17.5.2 Alternative Lattice Configuration

17.5.3 Digital Realization

17.6 Ladder Wave Digital Filters

17.7 Filters Satisfying Prescribed Specifications

17.8 Frequency-Domain Analysis

17.9 Scaling

17.10 Elimination of Limit-Cycle Oscillations

17.11 Related Synthesis Methods

17.12 A Cascade Synthesis Based on the Wave Characterization

17.12.1 Generalized-Immittance Converters

17.12.2 Analog G-CGIC Configuration

17.12.3 Digital G-CGIC Configuration

17.12.4 Cascade Synthesis

17.12.5 Signal Scaling

17.12.6 Output Noise

17.13 Choice of Structure

17.14 References

17.15 Problems

Chapter 18 Digital Signal Processing Applications

18.1 Introduction

18.2 Sampling-Frequency Conversion

18.2.1 Decimators

18.2.2 Interpolators

18.2.3 Sampling Frequency Conversion by a Noninteger Factor

18.2.4 Design Considerations

18.3 Quadrature Mirror-Image Filter Banks

18.3.1 Operation

18.3.2 Elimination of Aliasing Errors

18.3.3 Design Considerations

18.3.4 Perfect Reconstruction

18.4 Hilbert Transformers

18.4.1 Design of Hilbert Transformers

18.4.2 Single-Sideband Modulation

18.4.3 Sampling of Bandpassed Signals

18.5 Adaptive Digital Filters

18.5.1 Wiener Filters

18.5.2 Newton Algorithm

18.5.3 Steepest-Descent Algorithm

18.5.4 Least-Mean-Square Algorithm

18.5.5 Recursive Filters

18.5.6 Applications

18.6 Two-Dimensional Digital Filters

18.6.1 Two-Dimensional Convolution

- 18.6.2 Two-Dimensional z Transform
- 18.6.3 Two-Dimensional Transfer Function
- 18.6.4 Stability
- 18.6.5 Frequency-Domain Analysis
- 18.6.6 Types of 2-D Filters
- 18.6.7 Approximations
- 18.6.8 Applications

18.7 References

18.8 Additional References

18.9 Problems

Appendix A Complex Analysis

A.1 Introduction

A.2 Complex Numbers

- A.2.1 Complex Arithmetic
- A.2.2 De Moivre's Theorem
- A.2.3 Euler's Formula
- A.2.4 Exponential Form
- A.2.5 Vector Representation
- A.2.6 Spherical Representation

A.3 Functions of a Complex Variable

- A.3.1 Polynomials
- A.3.2 Inverse Algebraic Functions
- A.3.3 Trigonometric Functions and Their Inverses
- A.3.4 Hyperbolic Functions and Their Inverses
- A.3.5 Multi-Valued Functions
- A.3.6 Periodic Functions
- A.3.7 Rational Algebraic Functions

A.4 Basic Principles of Complex Analysis

- A.4.1 Limit
- A.4.2 Differentiability
- A.4.3 Analyticity

A.4.4 Zeros

A.4.5 Singularities

A.4.6 Zero-Pole Plots

A.5 Series

A.6 Laurent Theorem

A.7 Residue Theorem

A.8 Analytic Continuation

A.9 Conformal Transformations

A.10 References

Appendix B Elliptic Functions

B.1 Introduction

B.2 Elliptic Integral of the First Kind

B.3 Elliptic Functions

B.4 Imaginary Argument

B.5 Formulas

B.6 Periodicity

B.7 Transformation

B.8 Series Representation

B.9 References

Index