

Understanding Digital Signal Processing

Richard G. Lyons



PRENTICE HALL
Professional Technical Reference
Upper Saddle River, New Jersey 07458
www.phptr.com

Contents

Preface xi

1 DISCRETE SEQUENCES AND SYSTEMS 1

- 1.1 Discrete Sequences and Their Notation 2
- 1.2 Signal Amplitude, Magnitude, Power 8
- 1.3 Signal Processing Operational Symbols 9
- 1.4 Introduction to Discrete Linear Time-Invariant Systems 12
- 1.5 Discrete Linear Systems 12
- 1.6 Time-Invariant Systems 17
- 1.7 The Commutative Property of Linear Time-Invariant Systems 18
- 1.8 Analyzing Linear Time-Invariant Systems 19

2 PERIODIC SAMPLING 21

- 2.1 Aliasing: Signal Ambiguity in the Frequency Domain 21
- 2.2 Sampling Low-Pass Signals 26
- 2.3 Sampling Bandpass Signals 30
- 2.4 Spectral Inversion in Bandpass Sampling 39

3 THE DISCRETE FOURIER TRANSFORM 45

- 3.1 Understanding the DFT Equation 46
- 3.2 DFT Symmetry 58

3.3	DFT Linearity	60
3.4	DFT Magnitudes	61
3.5	DFT Frequency Axis	62
3.6	DFT Shifting Theorem	63
3.7	Inverse DFT	65
3.8	DFT Leakage	66
3.9	Windows	74
3.10	DFT Scalloping Loss	82
3.11	DFT Resolution, Zero Padding, and Frequency-Domain Sampling	83
3.12	DFT Processing Gain	88
3.13	The DFT of Rectangular Functions	91
3.14	The DFT Frequency Response to a Complex Input	112
3.15	The DFT Frequency Response to a Real Cosine Input	116
3.16	The DFT Single-Bin Frequency Response to a Real Cosine Input	117
3.17	Interpreting the DFT	120
4	THE FAST FOURIER TRANSFORM	125
4.1	Relationship of the FFT to the DFT	126
4.2	Hints on Using FFTs in Practice	127
4.3	FFT Software Programs	131
4.4	Derivation of the Radix-2 FFT Algorithm	132
4.5	FFT Input/Output Data Index Bit Reversal	139
4.6	Radix-2 FFT Butterfly Structures	141
5	FINITE IMPULSE RESPONSE FILTERS	151
5.1	An Introduction to Finite Impulse Response FIR Filters	152
5.2	Convolution in FIR Filters	157
5.3	Low-Pass FIR Filter Design	167
5.4	Bandpass FIR Filter Design	183
5.5	Highpass FIR Filter Design	184
5.6	Remez Exchange FIR Filter Design Method	186
5.7	Half-Band FIR Filters	188

5.8	Phase Response of FIR Filters	190
5.9	A Generic Description of Discrete Convolution	195
6	INFINITE IMPULSE RESPONSE FILTERS	211
6.1	An Introduction to Infinite Impulse Response Filters	212
6.2	The Laplace Transform	215
6.3	The z-Transform	228
6.4	Impulse Invariance IIR Filter Design Method	243
6.5	Bilinear Transform IIR Filter Design Method	259
6.6	Optimized IIR Filter Design Method	270
6.7	Pitfalls in Building IIR Digital Filters	272
6.8	Improving IIR Filters with Cascaded Structures	274
6.9	A Brief Comparison of IIR and FIR Filters	279
7	SPECIALIZED LOWPASS FIR FILTERS	283
7.1	Frequency Sampling Filters: The Lost Art	284
7.2	Interpolated Lowpass FIR Filters	319
8	QUADRATURE SIGNALS	335
8.1	Why Care About Quadrature Signals	336
8.2	The Notation of Complex Numbers	336
8.3	Representing Real Signals Using Complex Phasors	342
8.4	A Few Thoughts on Negative Frequency	346
8.5	Quadrature Signals in the Frequency Domain	347
8.6	Bandpass Quadrature Signals in the Frequency Domain	350
8.7	Complex Down-Conversion	352
8.8	A Complex Down-Conversion Example	354
8.9	An Alternate Down-Conversion Method	358
9	THE DISCRETE HILBERT TRANSFORM	361
9.1	Hilbert Transform Definition	362
9.2	Why Care About the Hilbert Transform?	364
9.3	Impulse Response of a Hilbert Transformer	369

9.4	Designing a Discrete Hilbert Transformer	371
9.5	Time-Domain Analytic Signal Generation	377
9.6	Comparing Analytical Signal Generation Methods	379
10	SAMPLE RATE CONVERSION	381
10.1	Decimation	382
10.2	Interpolation	387
10.3	Combining Decimation and Interpolation	389
10.4	Polyphase Filters	391
10.5	Cascaded Integrator-Comb Filters	397
11	SIGNAL AVERAGING	411
11.1	Coherent Averaging	412
11.2	Incoherent Averaging	419
11.3	Averaging Multiple Fast Fourier Transforms	422
11.4	Filtering Aspects of Time-Domain Averaging	430
11.5	Exponential Averaging	432
12	DIGITAL DATA FORMATS AND THEIR EFFECTS	439
12.1	Fixed-Point Binary Formats	439
12.2	Binary Number Precision and Dynamic Range	445
12.3	Effects of Finite Fixed-Point Binary Word Length	446
12.4	Floating-Point Binary Formats	462
12.5	Block Floating-Point Binary Format	468
13	DIGITAL SIGNAL PROCESSING TRICKS	471
13.1	Frequency Translation without Multiplication	471
13.2	High-Speed Vector-Magnitude Approximation	479
13.3	Frequency-Domain Windowing	484
13.4	Fast Multiplication of Complex Numbers	487
13.5	Efficiently Performing the FFT of Real Sequences	488
13.6	Computing the Inverse FFT Using the Forward FFT	500
13.7	Simplified FIR Filter Structure	503
13.8	Reducing A/D Converter Quantization Noise	503

13.9	A/D Converter Testing Techniques	510
13.10	Fast FIR Filtering Using the FFT	515
13.11	Generating Normally Distributed Random Data	516
13.12	Zero-Phase Filtering	518
13.13	Sharpened FIR Filters	519
13.14	Interpolating a Bandpass Signal	521
13.15	Spectral Peak Location Algorithm	523
13.16	Computing FFT Twiddle Factors	525
13.17	Single Tone Detection	528
13.18	The Sliding DFT	532
13.19	The Zoom FFT	541
13.20	A Practical Spectrum Analyzer	544
13.21	An Efficient Arctangent Approximation	547
13.22	Frequency Demodulation Algorithms	549
13.23	DC Removal	552
13.24	Improving Traditional CIC Filters	556
13.25	Smoothing Impulsive Noise	561
13.26	Efficient Polynomial Evaluation	563
13.27	Designing Very High-Order FIR Filters	564
13.28	Time-Domain Interpolation Using the FFT	568
13.29	Frequency Translation Using Decimation	571
13.30	Automatic Gain Control (AGC)	571
13.31	Approximate Envelope Detection	574
13.32	A Quadrature Oscillator	576
13.33	Dual-Mode Averaging	578

APPENDIX A. THE ARITHMETIC OF COMPLEX NUMBERS **585**

A.1	Graphical Representation of Real and Complex Numbers	585
A.2	Arithmetic Representation of Complex Numbers	586
A.3	Arithmetic Operations of Complex Numbers	588
A.4	Some Practical Implications of Using Complex Numbers	593

APPENDIX B. CLOSED FORM OF A GEOMETRIC SERIES **595**

APPENDIX C. TIME REVERSAL AND THE DFT **599**

APPENDIX D. MEAN, VARIANCE, AND STANDARD DEVIATION	603
D.1 Statistical Measures	603
D.2 Standard Deviation, or RMS, of a Continuous Sinewave	606
D.3 The Mean and Variance of Random Functions	607
D.4 The Normal Probability Density Function	610
APPENDIX E. DECIBELS (DB AND DBM)	613
E.1 Using Logarithms to Determine Relative Signal Power	613
E.2 Some Useful Decibel Numbers	617
E.3 Absolute Power Using Decibels	619
APPENDIX F. DIGITAL FILTER TERMINOLOGY	621
APPENDIX G. FREQUENCY SAMPLING FILTER DERIVATIONS	633
G.1 Frequency Response of a Comb Filter	633
G.2 Single Complex FSF Frequency Response	634
G.3 Multisection Complex FSF Phase	635
G.4 Multisection Complex FSF Frequency Response	636
G.5 Real FSF Transfer Function	638
G.6 Type-IV FSF Frequency Response	640
APPENDIX H. FREQUENCY SAMPLING FILTER DESIGN TABLES	643
INDEX	657
ABOUT THE AUTHOR	667