

The book cover features a dark, textured background with a prominent, jagged white lightning bolt running vertically down the center. The lightning bolt is surrounded by a soft, glowing orange and red aura. In the center, there is a dark rectangular box containing the author's name and the title.

CHI-TSONG CHEN

---

**DIGITAL SIGNAL PROCESSING**

SPECTRAL COMPUTATION AND FILTER DESIGN

# CONTENTS

---

Preface	xiii
<b>1 Introduction</b>	<b>1</b>
1.1 Continuous-Time (CT), Discrete-Time (DT), and Digital Signals	1
1.1.1 Plotting of DT Signals	3
1.2 Representation of Digital Signals	4
1.3 A/D and D/A Conversions	6
1.4 Comparison of Digital and Analog Techniques	11
1.5 Applications of Digital Signal Processing	12
1.6 Scope of the Book	14
1.6.1 Spectral Computation	15
1.6.2 Digital Filter Design	18
<b>PART 1 Spectral Computation</b>	
<b>2 CT and DT Fourier Series—Frequency Components</b>	<b>21</b>
2.1 Introduction	21
2.1.1 Frequency of CT Sinusoids	22
2.2 Frequency and Frequency Range of Sinusoidal Sequences	22
2.3 Frequencies of CT Sinusoids and Their Sampled Sequences	28
2.3.1 Applications	30
2.3.2 Recovering a Sinusoid from Its Sampled Sequence	31
2.4 Continuous-Time Fourier Series (CTFS)	34
2.4.1 Distribution of Average Power in Frequencies	42
2.4.2 Are Phases Important?	43
2.5 Discrete-Time Fourier Series (DTFS)	45
2.5.1 Range of Frequency Index $m$	51
2.5.2 Time Shifting	52
2.6 FFT Computation of DTFS Coefficients	54
2.6.1 Rearranging the Output of the FFT	55

2.7	FFT Computation of CTFS Coefficients	59
2.7.1	Frequency Aliasing due to Time Sampling	66
2.7.2	Selecting $N$ to Have Negligible Frequency Aliasing	69
2.8	Average Power and Its Computation	75
2.9	Concluding Remarks	78
	Problems	78
<b>3</b>	<b>CT and DT Fourier Transforms—Frequency Spectra</b>	<b>82</b>
3.1	Introduction	82
3.2	CT Fourier Transform (CTFT)	82
3.2.1	Frequency Spectrum of CT Periodic Signals	89
3.3	Properties of Frequency Spectra	92
3.3.1	Boundedness and Continuity	92
3.3.2	Even and Odd	93
3.3.3	Time Shifting	96
3.3.4	Frequency Shifting	96
3.3.5	Time Compression and Expansion	97
3.4	Distribution of Energy in Frequencies	99
3.5	Effects of Truncation	101
3.5.1	Gibbs Phenomenon	103
3.6	DT Fourier Transform (DTFT)	106
3.6.1	Frequency Spectrum of DT Periodic Signals	113
3.7	Effects of Truncation	114
3.8	Nyquist Sampling Theorem	117
3.8.1	Frequency Aliasing due to Time Sampling	122
3.9	Time-limited Bandlimited Theorem	126
3.9.1	Practical Reconstruction of $x(t)$ from $x(nT)$	127
	Problems	128
<b>4</b>	<b>DFT and FFT—Spectral Computation</b>	<b>132</b>
4.1	Introduction	132
4.2	Discrete Fourier Transform (DFT)	132
4.2.1	Relationship between DFT and DTFS	140
4.2.2	Inverse DFT and Inverse DTFT—Time Aliasing due to Frequency Sampling	141
4.3	Properties of DFT	144
4.3.1	Even and Odd	144
4.3.2	Periodic Shifting	145
4.4	Fast Fourier Transform (FFT)	146
4.4.1	Other FFT and DSP Processors	150
4.4.2	Real Sequences	152
4.5	Spectral Computation of Finite Sequences	155

4.5.1	Padding with Zeros	156
4.5.2	Spectral Computation of Infinite Sequences	159
4.6	Spectral Computation of CT Signals	163
4.6.1	Spectral Computation of CT Periodic Signals	171
4.7	Computing DT Signals from Spectra	174
4.7.1	Computing CT Signals from Spectra	179
4.8	Computing Energy Using FFT	182
4.9	Concluding Remarks	184
	Problems	186
<b>PART 2 Digital Filter Design</b>		
5	Linear Time-Invariant Lumped Systems	191
5.1	Introduction	191
5.2	Linearity and Time Invariance	192
5.2.1	LTI Systems—Convolutions	193
5.3	LTIL Systems—Difference Equations	198
5.3.1	Recursive and Nonrecursive Difference Equations	202
5.3.2	Sampling Period and Real-Time Processing	203
5.4	$z$ -Transform	204
5.4.1	Inverse $z$ -Transform	210
5.4.2	FFT Computation of the Inverse $z$ -Transform	213
5.5	Transfer Functions	215
5.5.1	Poles and Zeros	218
5.5.2	Transfer Functions of FIR and IIR Filters	222
5.5.3	DT Fourier Transform and $z$ -Transform	223
5.6	Stability	225
5.6.1	The Jury Test	226
5.7	Frequency Response	228
5.7.1	Infinite Time	234
5.7.2	Frequency Response and Frequency Spectrum	235
5.7.3	Alternative Derivation of Frequency Responses	237
5.8	Continuous-Time LTIL Systems	239
5.8.1	Laplace Transform and $z$ -Transform	241
5.9	CT Transfer Function, Stability, and Frequency Response	242
5.9.1	Measuring CT Frequency Responses	245
5.10	Concluding Remarks	247
	Problems	248
6	Ideal and Some Practical Digital Filters	252
6.1	Introduction	252

6.2	Ideal Digital Filters	252
6.3	Realizability	253
6.3.1	Filter Specifications	257
6.3.2	Digital Processing of Analog Signals	259
6.4	First-Order Digital Filters	261
6.4.1	Second-Order Digital Filters	270
6.5	Reciprocal Roots and All-Pass Filters	275
6.6	Miscellaneous Topics	280
6.6.1	Comb Filters	280
6.6.2	Sinusoid Generators	281
6.6.3	Goertzel Algorithm	284
6.7	Analog Ideal Low-Pass Filters	286
6.7.1	Why Antialiasing Filters?	289
	Problems	292
7	Design of FIR Filters	294
7.1	Introduction	294
7.2	Classification of Linear-Phase FIR Filters	295
7.3	Least-Squares Optimal Filters—Direct Truncation	302
7.4	Window Method	305
7.5	Desired Filters with Specified Transition Bands	310
7.5.1	Design by Frequency Sampling	313
7.6	Discrete Least-Squares Optimal FIR Filters	316
7.6.1	Integral Least-Squares Optimal FIR Filters	324
7.7	Minimax Optimal FIR Filters	327
7.8	Design of Digital Differentiators	332
7.9	Hilbert Transformers	340
7.9.1	From FIR Low-Pass Filters to Hilbert Transformers	346
7.10	A Design Example	349
	Problems	352
8	Design of IIR Filters	355
8.1	Introduction	355
8.2	Difficulties in Direct IIR Filter Design	356
8.3	Design of Analog Prototype Filters	358
8.4	Analog Frequency Transformations	364
8.5	Impulse Invariance Method	374
8.5.1	Digital Frequency Transformations	379
8.6	Bilinear Transformation	386
8.7	Analog-Prototype-to-Digital Transformations	390
8.8	Comparisons with FIR Filters	394
	Problems	395

<b>9 Structures of Digital Filters</b>	<b>398</b>
9.1 Introduction	398
9.2 Direct Form of FIR Filters	399
9.2.1 Cascade Form	400
9.3 DFT of Periodic Convolutions	403
9.3.1 FFT Computation of FIR Filters	404
9.3.2 Convolution of Finite and Infinite Sequences	408
9.4 Direct and Canonical Forms of IIR Filters	409
9.4.1 Implementation Using State-Space Equations	414
9.5 Effects of Filter Coefficient Quantizations	416
9.5.1 Dead Band and Limit Cycle	417
9.6 Cascade and Parallel Implementations	419
9.6.1 Implementation of Second-Order Sections	424
Problems	427
 Appendix: The Impulse	 431
 References	 435
Index	437