CONTENTS

PREFACE 19

1 INTRODUCTION 25

1.1 Modeling 25

1.2 Continuous-Time Physical Systems 28
Electric Circuits, 28
Operational Amplifier Circuits, 30
Simple Pendulum, 33
DC Power Supplies, 34
Analogous Systems, 36

1.3 Samplers and Discrete-Time Physical Systems 38
Analog-to-Digital Converter, 38
Numerical Integration, 40
Picture in a Picture, 41
Compact Discs, 42
Sampling in Telephone Systems, 43
Data-Acquisition System, 45

1.4 MATLAB and SIMULINK 46

2 CONTINUOUS-TIME SIGNALS AND SYSTEMS 47

2.1 Transformations of Continuous-Time Signals 48
Time Transformations, 48
Amplitude Transformations, 54

2.2 Signal Characteristics 56
Even and Odd Signals, 56
Periodic Signals, 58

2.3 Common Signals in Engineering 63

2.4 Singularity Functions 69
Unit Step Function, 69
Unit Impulse Function, 73

2.5 Mathematical Functions for Signals 78

2.6 Continuous-Time Systems 83
Interconnecting Systems, 85
Feedback System, 88

2.7 Properties of Continuous-Time Systems 89
Stability, 93
Linearity, 98

Summary 100
Problems 102

3 CONTINUOUS-TIME LINEAR TIME-INVARIANT SYSTEMS 114

3.1 Impulse Representation of Continuous-Time Signals 115

3.2 Convolution for Continuous-Time LTI Systems 116

3.3 Properties of Convolution 129

3.4 Properties of Continuous-Time LTI Systems 132
Memoryless Systems, 133
Invertibility, 133
Causality, 134
Stability, 135
Unit Step Response, 136

3.5 Differential-Equation Models 137
Solution of Differential Equations, 139
General Case, 141
Relation to Physical Systems, 143

3.6 Terms in the Natural Response 144
Stability, 145

3.7 System Response for Complex-Exponential Inputs 148
Linearity, 148
Complex Inputs for LTI Systems, 149
Impulse Response, 153

3.8 Block Diagrams 154
Direct Form I, 158
Direct Form II, 158

*n*th-Order Realizations, 158
Practical Considerations, 160

Summary 163
Problems 165

4 FOURIER SERIES 178

4.1 Approximating Periodic Functions 179
Periodic Functions, 179
Approximating Periodic Functions, 180

4.2 Fourier Series 184
Fourier Series, 185
Fourier Coefficients, 186

4.3 Fourier Series and Frequency Spectra 189
Frequency Spectra, 190

4.4 Properties of Fourier Series 199

4.5 System Analysis 202

4.6 Fourier Series Transformations 209
Amplitude Transformations, 210
Time Transformations, 212

Summary 214
Problems 215

5 THE FOURIER TRANSFORM 225

5.1 Definition of the Fourier Transform 225

5.2 Properties of the Fourier Transform 234
Linearity, 235
Time Scaling, 236
Time Shifting, 238
Time Reversal, 239
Time Transformation, 240
Duality, 242
Convolution, 244
Frequency Shifting, 245
Time Integration, 248
Time Differentiation, 250
Frequency Differentiation, 255
Symmetry, 256
Summary, 257

5.3 Fourier Transforms of Time Functions 257
DC Level, 257
Unit Step Function, 257
Switched Cosine, 258
Pulsed Cosine, 258
Exponential Pulse, 260
Fourier Transforms of Periodic Functions, 260
Summary, 265

5.4 Application of the Fourier Transform 265
Frequency Response of Linear Systems, 265
Frequency Spectra of Signals, 274
Summary, 276

5.5 Energy and Power Density Spectra 277
Energy Density Spectrum, 277
Power Density Spectrum, 280
Power and Energy Transmission, 282
Summary, 284

Summary 286
Problems 287

6 APPLICATIONS OF THE FOURIER TRANSFORM 296

6.1 Ideal Filters 296

6.2 Real Filters 303
RC Low-Pass Filter, 304
Butterworth Filter, 306
Bandpass Filters, 312
Active Filters, 313
Summary, 315

6.3 Bandwidth Relationships 316

6.4 Sampling Continuous-Time Signals 319
Impulse Sampling, 320
Shannon's Sampling Theorem, 323
Practical Sampling, 323

6.5 Reconstruction of Signals from Sample Data 324
Interpolating Function, 326
Digital-to-Analog Conversion, 328
Quantization Error, 330

6.6 Sinusoidal Amplitude Modulation 332
Frequency-Division Multiplexing, 341

6.7 Pulse-Amplitude Modulation 343
Time-Division Multiplexing, 345
Flat-Top PAM, 347

Summary 350
Problems 350

7 THE LAPLACE TRANSFORM 360

7.1 Definitions of Laplace Transforms 361

7.2 Examples 364

7.3 Laplace Transforms of Functions 369

7.4 Laplace Transform Properties 373
Real Shifting, 374
Differentiation, 378
Integration, 380

7.5 Additional Properties 381
Multiplication by t, 381
Initial Value, 382
Final Value, 383
Time Transformation, 384

7.6 Response of LTI Systems 387
Initial Conditions, 387
Transfer Functions, 388
Convolution, 393
Transforms with Complex Poles, 395
Functions with Repeated Poles, 398

7.7 LTI Systems Characteristics 399
Causality, 399
Stability, 400
Invertibility, 402
Frequency Response, 403
Step Response, 404

7.8 Bilateral Laplace Transform 406
Region of Convergence, 408
Bilateral Transform from Unilateral Tables, 410
Inverse Bilateral Laplace Transform, 413

7.9 Relationship of the Laplace Transform to the Fourier Transform 415

Summary 416
Problems 417

8 STATE VARIABLES FOR CONTINUOUS-TIME SYSTEMS 425

8.1 State-Variable Modeling 426

8.2 Simulation Diagrams 430

8.3 Solution of State Equations 436
Laplace-Transform Solution, 436
Convolution Solution, 441
Infinite Series Solution, 442

8.4 Properties of the State-Transition Matrix 445

8.5 Transfer Functions 447
Stability, 449

8.6 Similarity Transformations 451
Transformations, 451
Properties, 457

Summary 459
Problems 461

9 DISCRETE-TIME SIGNALS AND SYSTEMS 470

9.1 Discrete-Time Signals and Systems 472
Unit Step and Unit Impulse Functions, 474
Equivalent Operations, 476

9.2 Transformations of Discrete-Time Signals 477
Time Transformations, 478
Amplitude Transformations, 483

9.3 Characteristics of Discrete-Time Signals 486
Even and Odd Signals, 486
Signals Periodic in n, 489
Signals Periodic in Ω, 492

9.4 Common Discrete-Time Signals 493

9.5 Discrete-Time Systems 499
Interconnecting Systems, 500

9.6 Properties of Discrete-Time Systems 502
Systems with Memory, 502
Invertibility, 503
Inverse of a System, 504
Causality, 504
Stability, 505

Time Invariance, 505
Linearity, 506

Summary 508
Problems 510

10 DISCRETE-TIME LINEAR TIME-INVARIANT SYSTEMS 519

10.1 Impulse Representation of Discrete-Time Signals 520

10.2 Convolution for Discrete-Time Systems 521
Properties of Convolution, 530

10.3 Properties of Discrete-Time LTI Systems 533
Memory, 534
Invertibility, 534
Causality, 534
Stability, 535
Unit Step Response, 537

10.4 Difference-Equation Models 538
Difference-Equation Models, 538
Classical Method, 540
Solution by Iteration, 545

10.5 Terms in the Natural Response 546
Stability, 547

10.6 Block Diagrams 549
Two Standard Forms, 551

10.7 System Response for Complex-Exponential Inputs 555
Linearity, 556
Complex Inputs for LTI Systems, 556
Stability, 561
Sampled Signals, 561
Impulse Response, 561

Summary 563
Problems 564

11 THE *z*-TRANSFORM 576

11.1 Definitions of z-Transforms 576

11.2 Examples 579
Two z-Transforms, 579
Digital-Filter Example, 582

11.3 z-Transforms of Functions 584
Sinusoids, 585

11.4 z-Transform Properties 589
Real Shifting, 589
Initial and Final Values, 592

11.5 Additional Properties 594
Time Scaling, 594
Convolution in Time, 596

11.6 LTI System Applications 597
Transfer Functions, 597
Inverse z-Transform, 599
Complex Poles, 602
Causality, 604
Stability, 605
Invertibility, 608
Frequency Response, 609

11.7 Bilateral z-Transform 612
Bilateral Transforms, 616
Regions of Convergence, 618
Inverse Bilateral Transforms, 619

Summary 622
Problems 623

12 FOURIER TRANSFORMS OF DISCRETE-TIME SIGNALS 633

12.1 Discrete-Time Fourier Transform 634
z-Transform, 636

12.2 Properties of the Discrete-Time Fourier Transform 641
Periodicity, 642
Linearity, 643
Time Shift, 643
Frequency Shift, 644
Symmetry, 644
Time Reversal, 645
Convolution in Time, 645
Convolution in Frequency, 646
Multiplication by n, 647
Parseval's Theorem, 647

12.3 Discrete-Time Fourier Transform of Periodic Sequences 648

12.4 Discrete Fourier Transform 654
Shorthand Notation for the DFT, 656
Frequency Resolution of the DFT, 656
Validity of the DFT, 658
Summary, 662

12.5 Fast Fourier Transform 662
Decomposition-in-Time Fast Fourier Transform Algorithm, 662
Decomposition-in-Frequency Fast Fourier Transform, 667
Summary, 670

12.6 Applications of the Discrete Fourier Transform 670
Calculation of Fourier Transforms, 670
Convolution, 678
Filtering, 687
Correlation, 695
Energy Spectral Density Estimation, 701
Summary, 702

12.7 The Discrete Cosine Transform, 702

Summary 706
Problems 708

13 STATE VARIABLES FOR DISCRETE-TIME SYSTEMS 716

13.1 State-Variable Modeling 717

13.2 Simulation Diagrams 721

13.3 Solution of State Equations 727
Recursive Solution, 727
z-Transform Solution, 729

13.4 Properties of the State Transition Matrix 734

13.5 Transfer Functions 736
Stability, 738

13.6 Similarity Transformations 739
Properties, 743

Summary 744
Problems 745

APPENDICES 755

A. Integrals and Trigonometric Identities 755
Integrals, 755
Trigonometric Identities, 756

B. Leibnitz's and L'Hôpital's Rules 757
Leibnitz's Rule, 757
L'Hôpital's Rule, 758

C. Summation Formulas for Geometric Series 759

D. Complex Numbers and Euler's Relation 761
Complex-Number Arithmetic, 762
Euler's Relation, 765
Conversion Between Forms, 766

E. Solution of Differential Equations 769
Complementary Function, 769
Particular Solution, 770
General Solution, 771
Repeated Roots, 771

F. Partial-Fraction Expansions 773

G. Review of Matrices 777
Algebra of Matrices, 781
Other Relationships, 782

H. Answers to Selected Problems 785

I. Signals and Systems References 799

INDEX 805