

Contents

Preface xi

1 INTRODUCTION 1

| | |
|--|-----------|
| Introduction | 2 |
| 1.1 Basic Definitions | 3 |
| 1.2 Classification of Signals and Systems | 6 |
| 1.3 Frequency Spectrum in Signal and System Analysis | 9 |
| 1.4 Scope of the Text | 10 |
| <i>Summary</i> | <i>11</i> |
| <i>Further Reading</i> | <i>11</i> |
| <i>Problems</i> | <i>11</i> |

2 MATHEMATICAL MODELING AND PROPERTIES OF BASIC SIGNALS AND SYSTEMS 13

| | |
|---|-----------|
| Introduction | 14 |
| 2.1 Mathematical Modeling of Systems and Signals | 14 |
| 2.2 Basic Signal Operations and Properties | 18 |
| 2.3 Basic CT Signals | 39 |
| 2.4 Basic DT Signals | 54 |
| 2.5 Basic System Properties | 61 |
| 2.6 Frequency Response and CT Filters | 73 |
| 2.7 Discretization of CT Signal and System Models | 75 |
| 2.8 Linearization of Nonlinear Systems | 80 |
| <i>Summary</i> | <i>84</i> |
| <i>Key Equations</i> | <i>85</i> |
| <i>Further Reading</i> | <i>87</i> |
| <i>Problems</i> | <i>87</i> |

3 CONTINUOUS-TIME SYSTEM ANALYSIS IN TIME DOMAIN 97

| | |
|--|-----|
| Introduction | 98 |
| 3.1 Impulse-Response Characterization and the Convolution Integral for CT LTI Systems | 98 |
| 3.2 Step and Other Causal Signal Responses of CT LTI Systems | 103 |
| 3.3 Properties of Convolution | 109 |
| 3.4 LTI System Properties from Impulse Response | 121 |
| 3.5 Obtaining the Impulse Response of CT LTI Systems | 123 |
| 3.6 System Analysis from a Linear Differential-Equation Model | 125 |
| 3.7 CT System Response to Complex and Real Sinusoids and the System Function | 132 |
| 3.8 Block Diagram Representation for System Simulation | 138 |

| | |
|----------------------|-----|
| <i>Summary</i> | 142 |
| <i>Key Equations</i> | 143 |
| <i>Problems</i> | 144 |

4 DISCRETE-TIME SYSTEM ANALYSIS IN TIME DOMAIN 149

| | |
|---|-----|
| Introduction | 150 |
| 4.1 Impulse Response Characterization and the Convolution Summation | 150 |
| 4.2 Step and Other Causal Signal Response of DT LTI Systems | 156 |
| 4.3 Properties of the Convolution Summation | 161 |
| 4.4 Obtaining the Impulse Response of DT LTI Systems | 165 |
| 4.5 LTI System Properties from Impulse Response | 172 |
| 4.6 System Analysis from the Difference-Equation Model | 175 |
| 4.7 Forced Response to Complex and Real Sinusoids and the System Function | 183 |
| 4.8 Block Diagram Representation for System Simulation | 190 |
| <i>Summary</i> | 194 |
| <i>Key Equations</i> | 194 |
| <i>Further Reading</i> | 194 |
| <i>Problems</i> | 194 |

5 FREQUENCY DOMAIN ANALYSIS OF CT SIGNALS AND SYSTEMS—THE FOURIER SERIES AND FOURIER TRANSFORM ANALYSIS 205

| | |
|---|-----|
| Introduction | 206 |
| 5.1 Representation of Signals using Basis Functions | 206 |
| 5.2 Representation of Periodic Functions—The Exponential Fourier Series | 212 |
| 5.2.1 Existence of the Fourier Series | 217 |
| 5.2.2 Other Forms of the Fourier Series | 218 |
| 5.2.3 Frequency Spectrum of Periodic Signals | 222 |
| 5.2.4 Fourier Series Properties | 230 |
| 5.2.5 Fourier Series Representation of an Ideal Impulse Train | 232 |
| 5.2.6 System Analysis for Nonsinusoidal Periodic Inputs | 234 |
| 5.3 Frequency Spectrum of Aperiodic Signals—The Fourier Transform | 239 |
| 5.3.1 Existence of the Fourier Transform | 244 |
| 5.3.2 Fourier Transform of Basic Signals | 248 |
| 5.3.3 Fourier Transform Properties | 251 |
| 5.4 LTI System Analysis in the Frequency Domain | 281 |
| 5.5 Ideal and Practical Filters | 293 |
| <i>Summary</i> | 301 |
| <i>Key Equations</i> | 301 |
| <i>Further Reading</i> | 303 |
| <i>Problems</i> | 303 |

6 SYSTEM ANALYSIS USING THE LAPLACE TRANSFORM 315

| | |
|--|-----|
| Introduction | 316 |
| 6.1 The Bilateral and Unilateral Laplace Transforms | 316 |
| 6.2 Laplace Transforms of Basic Signals | 320 |
| 6.3 Laplace Transform Properties | 321 |
| 6.4 Relationship between Fourier and Laplace Transforms | 339 |
| 6.5 The Inverse Laplace Transform | 340 |
| 6.6 Applications of the Laplace Transform in Solving Differential Equations | 352 |
| 6.7 LTI System Transfer Function | 355 |
| 6.8 System Response and Stability from Transfer Functions | 364 |
| 6.9 Step Response of Stable Systems | 377 |
| 6.10 Sinusoidal Response of Stable Systems and the Frequency Response | 385 |
| 6.11 Bode Plots | 396 |
| 6.12 System Simulation | 410 |
| <i>Summary</i> | 412 |
| <i>Key Equations</i> | 413 |
| <i>Further Reading</i> | 414 |
| <i>Problems</i> | 415 |

7 THE z-TRANSFORM AND DISCRETE-TIME SYSTEM ANALYSIS 425

| | |
|--|-----|
| Introduction | 426 |
| 7.1 The z-Transform | 426 |
| 7.2 Convergence of the z-Transform | 429 |
| 7.3 Basic z-Transforms | 435 |
| 7.4 Properties of the z-Transform | 437 |
| 7.4.1 Right- and Left-Shifted Signals | 437 |
| 7.4.2 Multiplication by an Exponential Signal | 441 |
| 7.4.3 Differentiation in the z-Domain | 443 |
| 7.4.4 Accumulation | 444 |
| 7.4.5 Convolution of Signals | 445 |
| 7.4.6 Initial Value | 447 |
| 7.4.7 Time Reversal | 447 |
| 7.5 The Inverse z-Transform | 450 |
| 7.5.1 Pole-Zero Plots and Inverse of Rational Functions of z | 450 |
| 7.5.2 Inverse z-Transform from a Power Series Expansion | 460 |
| 7.6 Solving Difference Equations using z-Transforms | 463 |
| 7.7 DT LTI System Characterization | 465 |
| 7.7.1 DT LTI System Transfer Functions from Impulse-Response Characterization | 465 |
| 7.7.2 Transfer Functions from Difference-Equation Models | 467 |
| 7.7.3 System Properties and Modes from $H(z)$ | 469 |
| 7.8 Frequency Response of DT Systems | 474 |
| 7.9 Representation of Discrete-Time Systems for Implementation | 483 |

7.10 The z-Transform of Sampled Signals—Relationship to the Laplace Transform 490

Summary 492

Key Equations 493

Further Reading 494

Problems 494

8 FREQUENCY DOMAIN ANALYSIS OF DT SIGNALS AND SYSTEMS—THE DTFT AND DFT ANALYSIS 503

Introduction 504

8.1 Spectrum of Sampled Signals and the Sampling Theorem 504

8.1.1 Aliasing 509

8.1.2 Signal Reconstruction 511

8.2 The Discrete-Time Fourier Transform 512

8.3 Properties of the Discrete-Time Fourier Transform 519

8.4 Frequency-Domain Analysis of DT Systems 529

8.5 Discrete Fourier Transform and its Properties 533

8.6 Applications of the DFT in Signal and System Analysis 546

Summary 552

Key Equations 552

Further Reading 553

Problems 554

9 STATE VARIABLE ANALYSIS OF CONTINUOUS- AND DISCRETE-TIME SYSTEMS 559

Introduction 560

9.1 State-Variable Representation and Analysis of CT Systems 560

9.1.1 Construction of State-Variable Models from System Configurations 563

9.1.2 Conversion of Differential-Equation Models to State-Variable Models 565

9.1.3 Obtaining State-Variable Models from Block Diagrams and Transfer Functions 568

9.1.4 System Analysis in Time and s-Domains Using State-Variable Models 578

9.1.5 MATLAB Applications 587

9.2 State Variable Representation and Analysis of DT Systems 591

9.2.1 Obtaining State-Variable Models from Block Diagrams 593

9.2.2 Conversion of Transfer-Function and Difference-Equation Models to State-Variable Models 595

9.2.3 System Analysis in Time and z-domains Using State Variable Models 600

9.2.4 MATLAB Applications 606

| | |
|------------------------|-----|
| <i>Summary</i> | 610 |
| <i>Key Equations</i> | 611 |
| <i>Further Reading</i> | 612 |
| <i>Problems</i> | 612 |

| | |
|----------|-----|
| APPENDIX | 619 |
|----------|-----|

| | | |
|---|--|-----|
| A | Complex Numbers | 619 |
| | A.1 Representation | 619 |
| | A.2 Operations on Complex Numbers | 623 |
| B | Some Useful Mathematical Operations | 627 |
| | B.1 Combining Cosine and Sine Terms into a Cosine Term | 627 |
| | B.2 Magnitude and Phase of $H(v) = 1 + e^{j\alpha v}$ | 628 |
| | B.3 Product Rule for Integration/Integration by Parts | 629 |
| | B.4 Derivative of an Integral—Leibnitz's Rule | 629 |
| | B.5 L'Hospital's Rule of Finding Limits | 629 |
| | B.6 Partial-Fraction Expansion | 630 |
| | B.7 Finite and Infinite Series Summations | 633 |
| | B.8 Minimum Squared Error ¹ | 635 |
| C | Basic Matrix Operations | 639 |
| | C.1 Definitions | 639 |
| | C.2 Matrix Operations | 641 |
| D | Mathematical Tables | 643 |
| | D.1 Trigonometric Identities | 643 |
| | D.2 Derivatives | 643 |
| | D.3 Integrals | 643 |