CONTENTS

Preface *vii*
List of Symbols *xxi*
List of Abbreviations *xxii*

CHAPTER 1: Introduction to Signals and Systems **1.1–1.8**

1.1 Signals 1.1
1.1.1 Continuous Time Signal 1.2
1.1.2 Discrete Time Signal 1.2
1.1.3 Digital Signal 1.2
1.2 Systems 1.3
1.2.1 Continuous Time System 1.3
1.2.2 Discrete Time System 1.4
1.3 Frequency Domain Analysis of Continuous Time Signals and Systems 1.5
1.4 Frequency Domain Analysis of Discrete Time Signals and Systems 1.6
1.5 Importance of Signals and Systems 1.6
1.6 Use of MATLAB in Signals and Systems 1.8

CHAPTER 2: Continuous Time Signals and Systems **2.1–2.42**

2.1 Introduction 2.1
2.2 Standard Continuous Time Signals 2.1
2.2.1 Periodic Continuous Time Signals 2.3
2.3 Impulse Signal 2.5
2.3.1 Properties of Impulse Signal 2.6
2.3.2 Representation of a Continuous Time Signal as Integral of Impulses 2.8
2.4 Mathematical Operations on Continuous Time Signals 2.11
2.4.1 Order of Mathematical Operations on Signals with Multiple Operations 2.18
2.5 Classification of Continuous Time Signals 2.26
2.5.1 Deterministic and Nondeterministic (Random or Stochastic) Signals 2.26
2.5.2 Periodic and Nonperiodic Signals 2.26
2.5.3 Symmetric (Even) and Antisymmetric (Odd) Signals 2.33
2.5.4 Energy and Power Signals 2.38
2.5.5 Causal, Noncausal and Anticausal Signals 2.43
2.6 Continuous Time System (Analog System) 2.44
2.6.1 Linear Time Invariant (LTI) System 2.44

2.6.2 Response of a Continuous Time System 2.44
2.6.3 Impulse Response 2.45
2.6.4 Unit Step Response 2.45
2.6.5 Differential Equation Governing LTI Continuous Time System 2.45
2.6.6 Block Diagram and Signal Flow Graph Representation of Continuous Time System in Time Domain 2.46
2.7 Response of LTI Continuous Time System in Time Domain 2.49
2.7.1 Homogeneous Solution 2.50
2.7.2 Particular Solution 2.51
2.7.3 Zero-Input and Zero-State Response 2.52
2.7.4 Total Response 2.52
2.8 Classification of Continuous Time Systems 2.57
2.8.1 Static and Dynamic Systems 2.58
2.8.2 Time Invariant and Time Variant Systems (Shift Invariant and Shift Variant Systems) 2.58
2.8.3 Linear and Nonlinear Systems 2.61
2.8.4 Causal and Noncausal Systems (Realizable and Nonrealizable System) 2.65
2.8.5 Stable and Unstable Systems 2.68
2.8.6 Feedback and Nonfeedback Systems 2.73
2.8.7 Invertible and Noninvertible Systems 2.73
2.9 Convolution of Continous Time Signals (Convolution Integral) 2.81
2.9.1 Response of LTI Continuous Time System Using Convolution 2.81
2.9.2 Properties of Convolution 2.82
2.9.3 Convolution of Impulse Signal 2.84
2.9.4 Interconnection of Continuous Time Systems 2.84
2.9.5 Procedure to Perform Convolution 2.86
2.9.6 Unit Step Response Using Convolution 2.86
2.10 Inverse System and Deconvolution 2.107
2.11 Correlation, Crosscorrelation and Autocorrelation 2.108
2.11.1 Correlation (Crosscorrelation) 2.108
2.11.2 Autocorrelation 2.109
2.11.3 Properties of Crosscorrelation 2.109
2.11.4 Properties of Autocorrelation 2.110
2.12 Summary of Important Concepts 2.112
2.13 Short-Answer Questions 2.113
2.14 MATLAB Programs 2.123
2.15 Exercises 2.132

CHAPTER 3: Laplace Transform 3.1–3.154

3.1 Laplace Transform 3.1
3.1.1 s-Plane (or Complex Frequency Plane) 3.2
3.1.2 Definition of Laplace Transform 3.2

3.1.3 Existence of Laplace Transform 3.3
3.1.4 Poles and Zeros of Rational Function of s 3.3
3.2 Region of Convergence 3.5
3.2.1 ROC of Continuous Time Signal 3.5
3.2.2 ROC of Rational Function of s (ROC Using Poles) 3.7
3.2.3 Properties of ROC 3.9
3.3 Properties and Theorems of Laplace Transform 3.28
3.4 Inverse Laplace Transform 3.51
3.4.1 Inverse Laplace Transform by Partial Fraction Expansion Method 3.51
3.4.2 Inverse Laplace Transform Using Convolution Theorem 3.57
3.5 Analysis of LTI Continuous Time System Using Laplace Transform 3.67
3.5.1 Transfer Function of LTI Continuous Time System 3.67
3.5.2 Impulse Response and Transfer Function 3.68
3.5.3 Response of LTI Continuous Time System Using Laplace Transform 3.69
3.5.4 Convolution and Deconvolution Using Laplace Transform 3.70
3.5.5 Stability in s-Domain 3.71
3.5.6 Eigen Values and Eigen Function of LTI Continuous Time Systems 3.77
3.6 Block Diagram Representation of LTI Continuous Time Systems in s-Domain 3.105
3.6.1 Direct Form-I Structure 3.106
3.6.2 Direct Form-II Structure 3.107
3.6.3 Cascade Structure 3.110
3.6.4 Parallel Structure 3.111
3.7 Summary of Important Concepts 3.129
3.8 Short-Answer Questions 3.130
3.9 MATLAB Programs 3.135
3.10 Exercises 3.142

CHAPTER 4: Fourier Series and Fourier Transform of Continuous Time Signals 4.1–4.130

4.1 Introduction 4.1
4.1.1 Trigonometric Form of Fourier Series 4.1
4.1.2 Dirichlet's Conditions for Existence of Fourier Series 4.2
4.1.3 Exponential Form of Fourier Series 4.3
4.1.4 Negative Frequency 4.3
4.1.5 Convertion of Trigonometric to Fourier Coefficients 4.4
4.1.6 Derivation of Equations for a_0, a_n, b_n and c_n 4.5
4.1.7 Properties of Fourier Series 4.9
4.2 Fourier Coefficients of Signals with Symmetry 4.10
4.2.1 Even Symmetry 4.10
4.2.2 Odd Symmetry 4.11

4.2.3 Half Wave Symmetry (or Alternation Symmetry) 4.13
4.2.4 Quarter Wave Symmetry 4.13
4.3 Diminishing of Fourier Coefficients 4.18
4.4 Gibbs Phenomenon 4.19
4.5 Spectrum of Continuous Time Signals from Fourier Series 4.20
4.6 Solved Problems in Fourier Series 4.21
4.7 Fourier Transform 4.49
4.7.1 Development of Fourier Transform from Fourier Series 4.49
4.7.2 Definition of Fourier Transform 4.51
4.7.3 Conditions for Existence of Fourier Transform (Dirichlet's Condition) 4.51
4.7.4 Definition of Inverse Fourier Transform 4.51
4.7.5 Frequency Spectrum Using Fourier Transform 4.52
4.7.6 Properties of Fourier Transform 4.52
4.7.7 Comparison of Fourier Series and Fourier Transform 4.62
4.8 Fourier Transform of Some Important Signals 4.62
4.8.1 Fourier Transform of Unit Impulse Signal 4.62
4.8.2 Fourier Transform of Single-Sided Exponential Signal 4.62
4.8.3 Fourier Transform of Double-Sided Exponential Signal 4.63
4.8.4 Fourier Transform of a Constant (Fourier Transform of DC Signal) 4.64
4.8.5 Fourier Transform of Signum Function 4.65
4.8.6 Fourier Transform of Unit Step Signal 4.66
4.8.7 Fourier Transform of Complex Exponential Signal 4.67
4.8.8 Fourier Transform of Sinusoidal Signal 4.68
4.8.9 Fourier Transform of Cosinusoidal Signal 4.68
4.8.10 Fourier Transform of Gaussian Pulse 4.69
4.8.11 Fourier Transform of Exponentially Decaying Cosinusoidal Signal 4.69
4.8.12 Fourier Transform of Rectangular Pulse 4.70
4.8.13 Fourier Transform of Sinc Signal 4.71
4.8.14 Fourier Transform of Shifted impulse 4.72
4.9 Solved Problems in Fourier Transform 4.78
4.10 Fourier Transform of a Periodic Signal 4.93
4.11 Analysis of LTI Continuous Time System Using Fourier Transform 4.95
4.11.1 Transfer Function of LTI Continuous Time System in Frequency Domain 4.95
4.11.2 Impulse Response and Transfer Function 4.96
4.11.3 Response of LTI Continuous Time System Using Fourier Transform 4.97
4.11.4 Impulse Response and Frequency Response of LTI Continuous Time System 4.97
4.12 Relation between Fourier Transform and Laplace Transform 4.103
4.13 Summary of Important Concepts 4.105
4.14 Short-Answer Questions 4.105
4.15 MATLAB Programs 4.118
4.16 Exercises 4.122

CHAPTER 5: State Space Analysis of Continuous Time Systems 5.1–5.26

5.1 Introduction 5.1
5.2 State Model of a Continuous Time System 5.1
5.3 State Model of a Continuous Time System from Direct Form-II Structure 5.4
5.4 Transfer Function of a Continuous Time System from State Model 5.5
5.5 Solution of State Equations and Response of Continuous Time System 5.6
5.6 Solved Problems in State Space Analysis 5.8
5.7 Summary of Important Concepts 5.17
5.8 Short-Answer Questions 5.17
5.9 MATLAB Programs 5.20
5.10 Exercises 5.21

CHAPTER 6: Discrete Time Signals and Systems 6.1–6.184

6.1 Discrete Time Signals 6.1
- 6.1.1 Generation of Discrete Time Signals 6.1
- 6.1.2 Digital Signal 6.2
- 6.1.3 Representation of Discrete Time Signals 6.4
- 6.1.4 Concept of Frequency in Discrete Time Signals 6.5
- 6.1.5 Standard Discrete Time Signals 6.6
- 6.1.6 Representation of a Discrete Time Signal as Summation of Impulses 6.9
- 6.1.7 Mathematical Operations on Discrete Time Signals 6.10

6.2 Sampling Techniques 6.17
- 6.2.1 Baseband Sampling 6.19
- 6.2.2 Sampling and Aliasing 6.20

6.3 Classification of Discrete Time Signals 6.24
- 6.3.1 Deterministic and Nondeterministic (Random) Signals 6.24
- 6.3.2 Periodic and Nonperiodic Signals 6.25
- 6.3.3 Symmetric (Even) and Antisymmetric (Odd) Signals 6.30
- 6.3.4 Energy and Power Signals 6.33
- 6.3.5 Causal, Noncausal and Anticausal Signals 6.36
- 6.3.6 Absolutely Summable and Nonsummable Signals 6.36

6.4 Discrete Time System 6.37
- 6.4.1 Linear Time Invariant (LTI) System 6.37
- 6.4.2 Response of Discrete Time System 6.37
- 6.4.3 Impulse and Step Response 6.38
- 6.4.4 Difference Equation Governing Discrete Time System (Mathematical Representation of Discrete Time System) 6.38

6.5 Block Diagram and Signal Flow Graph Representation of Discrete Time System 6.39
6.6 Response of LTI Discrete Time System in Time Domain 6.42
- 6.6.1 Zero-Input Response or Homogeneous Solution 6.42
- 6.6.2 Particular Solution 6.43

6.6.3 Zero-State Response 6.44
6.6.4 Total Response 6.44
6.7 Classification of Discrete Time Systems 6.48
6.7.1 Static and Dynamic Systems 6.49
6.7.2 Time Invariant and Time Variant Systems (Shift Invariant and Shift Variant Systems) 6.49
6.7.3 Linear and Nonlinear Systems 6.53
6.7.4 Causal and Noncausal Systems (Realizable and Nonrealizeable System) 6.60
6.7.5 Stable and Unstable Systems 6.62
6.7.6 FIR and IIR Systems 6.66
6.7.7 Recursive and Nonrecursive Systems 6.67
6.7.8 Invertible and Noninvertible Systems 6.67
6.8 Convolution Sum 6.83
6.8.1 Discrete or Linear Convolution 6.83
6.8.2 Representation of Discrete Time Signal as Summation of Impulses 6.85
6.8.3 Response of LTI Discrete Time System Using Discrete Convolution 6.86
6.8.4 Properties of Linear Convolution 6.87
6.8.5 Methods of Performing Linear Convolution 6.88
6.8.6 Convolution of Impulse Signal 6.90
6.8.7 Unit Step Response Using Convolution 6.90
6.9 Interconnections of Discrete Time Systems 6.102
6.9.1 Cascade Connected Discrete Time Systems 6.102
6.9.2 Parallel Connected Discrete Time Systems 6.102
6.10 Circular Convolution 6.109
6.10.1 Circular Representation and Circular shift of Discrete Time Signal 6.109
6.10.2 Circular Symmetries of Discrete Time Signal 6.111
6.10.3 Definition of Circular Convolution 6.112
6.10.4 Procedure for Evaluating Circular Convolution 6.113
6.10.5 Linear Convolution via Circular Convolution 6.113
6.10.6 Methods of Computing Circular Convolution 6.114
6.11 Sectioned Convolution 6.123
6.11.1 Overlap Add Method 6.124
6.11.2 Overlap Save Method 6.124
6.12 Inverse System and Deconvolution 6.140
6.12.1 Inverse System 6.140
6.12.2 Deconvolution 6.141
6.13 Correlation, Crosscorrelation and Autocorrelation 6.143
6.13.1 Procedure for Evaluating Correlation 6.144
6.14 Circular Correlation 6.153
6.14.1 Procedure for Evaluating Circular Correlation 6.153
6.14.2 Methods of Computing Circular Correlation 6.154
6.15 Summary of Important Concepts 6.158
6.16 Short-Answer Questions 6.159

6.17 MATLAB Programs 6.169
6.18 Exercises 6.174

CHAPTER 7: ℤ-Transform 7.1–7.138

7.1 Introduction 7.1
- 7.1.1 z-Plane 7.1
- 7.1.2 Definition of ℤ-Transform 7.1
- 7.1.3 Inverse ℤ-Transform 7.3
- 7.1.4 Poles and Zeros of Rational Function of z 7.4

7.2 Region of Convergence of ℤ-Transform 7.6
- 7.2.1 ROC of Discrete Time Signals 7.6
- 7.2.2 ROC of Rational Function of z (ROC Using Poles) 7.11
- 7.2.3 Properties of ROC 7.12

7.3 Properties of ℤ-Transform 7.19

7.4 Various Methods of Computing Inverse ℤ-Transform 7.41
- 7.4.1 Inverse ℤ-Transform by Contour Integration or Residue Method 7.41
- 7.4.2 Inverse ℤ-Transform by Partial Fraction Expansion Method 7.42
- 7.4.3 Inverse ℤ-Transform by Power Series Expansion Method (Long Division Method) 7.45

7.5 Analysis of LTI Discrete Time System Using ℤ-transform 7.71
- 7.5.1 Transfer Function of LTI Discrete Time Systems 7.71
- 7.5.2 Impulse Response and Transfer Function 7.72
- 7.5.3 Response of LTI Discrete Time System Using ℤ-Transform 7.72
- 7.5.4 Convolution and Deconvolution Using ℤ-Transform 7.74
- 7.5.5 Stability in z-Domain 7.74

7.6 Relation between Laplace Transform and ℤ-Transform 7.80
- 7.6.1 Impulse Train Sampling of Continuous Time Signals 7.80
- 7.6.2 Transformation from Laplace Transform to ℤ-Transform 7.80
- 7.6.3 Relation between s-Plane and z-Plane 7.81

7.7 Structures for Realization of LTI Discrete Time Systems in z-Domain 7.114

7.8 Eigen Function and Eigen Value of LTI Discrete Time Systems 7.115

7.9 Summary of Important Concepts 7.117

7.10 Short-Answer Questions 7.118

7.11 MATLAB Programs 7.127

7.12 Exercises 7.132

CHAPTER 8: Fourier Series and Fourier Transform of Discrete Time Signals 8.1–8.102

8.1 Introduction 8.1

8.2 Fourier Series of Discrete Time Signals (Discrete Time Fourier Series) 8.1
- 8.2.1 Frequency Spectrum of Periodic Discrete Time Signals 8.3
- 8.2.2 Properties of Discrete Time Fourier Series 8.4

8.3 Fourier Transform of Discrete Time Signals (Discrete Time Fourier Transform) 8.16
8.3.1 Development of Discrete Time Fourier Transform from Discrete Time Fourier Series 8.16
8.3.2 Definition of Discrete Time Fourier Transform 8.17
8.3.3 Frequency Spectrum of Discrete Time Signal 8.18
8.3.4 Inverse Discrete Time Fourier Transform 8.19
8.3.5 Comparison of Fourier Transform of Discrete and Continuous Time Signals 8.20
8.3.6 Properties of Discrete Time Fourier Transform 8.20
8.3.7 Spectral Density 8.29
8.4 Discrete Time Fourier Transform of Periodic Discrete Time Signals 8.31
8.5 Analysis of LTI Discrete Time Systems in Frequency Domain 8.32
8.5.1 Transfer Function of LTI Discrete Time Systems in Frequency Domain 8.32
8.5.2 Impulse Response and Transfer Function 8.32
8.5.3 Response of LTI Discrete Time System for Nonperiodic Inputs 8.33
8.5.4 Response of LTI Discrete Time Systems for Periodic Inputs 8.33
8.5.5 Impulse Response and Frequency Response of LTI Discrete Time Systems 8.34
8.5.6 Properties of Frequency Response 8.35
8.5.7 Frequency Response of First-Order Discrete Time Systems 8.36
8.5.8 Frequency Response of Second-Order Discrete Time Systems 8.42
8.6 Relation between Continuous Time and Discrete Time Systems 8.47
8.6.1 Spectra of Sampled Signal 8.47
8.6.2 Aliasing in Frequency Spectrum Due to Sampling 8.49
8.6.3 Antialaising Filter 8.49
8.6.4 Sampling of Bandpass Signal 8.49
8.6.5 Signal Reconstruction (Recovery of Continuous Time Signal) 8.50
8.6.6 Hold Circuits 8.51
8.7 Relation between $\mathcal{Z}$-Transform and Discrete Time Fourier Transform 8.52
8.8 Summary of Important Concepts 8.85
8.9 Short-Answer Questions 8.86
8.10 MATLAB Programs 8.91
8.11 Exercises 8.96

CHAPTER 9: Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) 9.1–9.76

9.1 Introduction 9.1
9.2 Discrete Fourier Transform (DFT) of Discrete Time Signals 9.1
9.2.1 Frequency Domain Sampling 9.1
9.2.2 Development of DFT from DTFT 9.4
9.2.3 Definition of Discrete Fourier Transform (DFT) 9.4
9.2.4 Frequency Spectrum Using DFT 9.5
9.2.5 Inverse DFT 9.6

9.3 Properties of DFT 9.6
9.3.1 Periodicity 9.6
9.3.2 Symmetry 9.6
9.3.3 Circular Convolution 9.10
9.3.4 Linearity 9.11
9.3.5 Circular Time Shift 9.12
9.3.6 Time Reversal 9.12
9.3.7 Conjugation 9.12
9.3.8 Circular Freqeuncy Shift 9.13
9.3.9 Multiplication 9.13
9.3.10 Circular Correlation 9.14
9.3.11 Parseval's Relation 9.15
9.4 Relation between DFT and z-Transform 9.15
9.5 Analysis of LTI Discrete Time Systems Using DFT 9.16
9.5.1 Discrete Frequency Spectrum 9.17
9.5.2 Linear Convolution Using DFT 9.17
9.5.3 Response of LTI Discrete Time System Using DFT 9.17
9.6 Fast Fourier Transform (FFT) 9.28
9.7 Decimation in Time (DIT) Radix-2 FFT 9.31
9.7.1 8-Point DFT Using Radix-2 DIT FFT 9.33
9.7.2 Flow Graph for 8-Point DFT Using Radix-2 DIT FFT 9.37
9.8 Decimation in Frequency (DIF) Radix-2 FFT 9.39
9.8.1 8-point DFT Using Radix-2 DIF FFT 9.42
9.8.2 Flow Graph for 8-point DFT Using Radix-2 DIF FFT 9.44
9.8.3 Comparison of DIT and DIF Radix-2 FFT 9.47
9.9 Computation of Inverse DFT Using FFT 9.47
9.10 Summary of Important Concepts 9.62
9.11 Short-Answer Questions 9.63
9.12 MATLAB Programs 9.66
9.13 Exercises 9.72

CHAPTER 10: Structures for Realization of IIR and FIR Systems 10.1–10.56

10.1 Introduction 10.1
10.2 Discrete Time IIR and FIR Systems 10.1
10.2.1 Discrete Time IIR Systems 10.2
10.2.2 Discrete Time FIR Systems 10.2
10.3 Structures for Realization of IIR Systems 10.3
10.3.1 Direct Form-I Structure of IIR Systems 10.4
10.3.2 Direct Form-II Structure of IIR Systems 10.5
10.3.3 Cascade Form Realization of IIR Systems 10.8
10.3.4 Parallel Form Realization of IIR Systems 10.8

10.4 Structures for Realization of FIR Systems 10.37
10.4.1 Direct Form Realization of FIR Systems 10.37
10.4.2 Cascade Form Realization of FIR Systems 10.38
10.4.3 Linear Phase Realization of FIR Systems (Realization with Minimum Number of Multipliers) 10.39
10.5 Summary of Important Concepts 10.44
10.6 Short-Answer and Questions 10.46
10.7 Exercises 10.48

CHAPTER 11: State Space Analysis of Discrete Time Systems 11.1–11.24

11.1 Introduction 11.1
11.2 State Model of Discrete Time System 11.1
11.3 State Model of a Discrete Time System from Direct Form-II Structure 11.4
11.4 Transfer Function of a Discrete Time System from State Model 11.5
11.5 Solution of State Equations and Response of Discrete Time System 11.6
11.6 Solved Problems in State Space Analysis of Discrete Time Systems 11.8
11.7 Summary of Important Concepts 11.15
11.8 Short-Answer Questions 11.16
11.9 MATLAB Programs 11.18
11.10 Exercises 11.20

QUESTION PAPERS Q.1–Q.28

APPENDICES A.1–A.22

Appendix 1: Important Mathematical Relations A.1
Appendix 2: MATLAB Commands and Functions A.4
Appendix 3: Summary of Various Standard Transform Pairs A.9
Appendix 4: Summary of Properties of Various Transforms A.15

INDEX I.1 – I.8