## **Contents**

Pro	eface		xv	
Ac	Acknowledgements  List of Symbols and Abbreviations			
Lis	t of Symb	ols and Abbreviations	xx	
		Chapter 1: Introduction to Signals and Systems		
1.1	Signal		1. 1	
	1.1.1	Continuous Time Signal 1. 2		
	1.1. 2	Discrete Time Signal 1. 2		
	1.1.3	Digital Signal 1. 3		
1.2	Systen	1	1. 3	
	1.2.1	Continuous Time System 1. 3		
	1.2.2	Discrete Time System 1. 4		
1.3	Freque	ncy Domain Analysis of Continuous Time Signals and Systems	1. 5	
1.4	Freque	ncy Domain Analysis of Discrete Time Signals and Systems	1. 6	
1.5	Import	ance of Signals and Systems	1. 7	
1.6	Use of	MATLAB in Signals and Systems	1. 8	
		Chapter 2: Continuous Time Signals and Systems		
2.1	Introd	action	2. 1	
2.2	Standa	rd Continuous Time Signals	2. 1	
2.3	Classif	ication of Continuous Time Signals	2. 6	
	2.3.1	Deterministic and Nondeterministic Signals 2. 6		
	2.3.2	Periodic and Nonperiodic Signals 2. 6		
	2.3.3	Symmetric (Even) and Antisymmetric (Odd) Signals 2. 11		
	2.3.4	Energy and Power Signals 2. 13		
	2.3.5	Causal, Noncausal and Anticausal Signals 2. 15		
2.4	Mathe	matical Operations on Continuous Time Signals	2. 16	
	2.4.1	Scaling of Continuous Time Signals 2. 16		
	2.4.2	Folding (Reflection or Transpose) of Continuous Time Signals 2. 18		
	2.4.3	Time Shifting of Continuous Time Signals 2. 18		
	2.4.4	Addition of Continuous Time Signals 2. 20		
	2.4.5	Multiplication of Continuous Time Signals 2. 20		
	2.4.6	Differentiation and Integration of Continuous Time Signals 2. 21		
2.5	Impuls	e Signal	2. 24	
	2.5.1	Properties of Impulse Signal 2. 25		
	2.5.2	Representation of Continuous Time Signal as Integral of Impulses 2. 27		
2.6	Continuous Time System			
	2.6.1	Mathematical Equation Governing LTI Continuous Time System 2. 29		
	2.6.2	Block Diagram and Signal Flow Graph Representation of LTI Continuous Time System	2. 31	

viii Contents

2.7	Response of LTI Continuous Time System in Time Domain	2. 34	
	2.7.1 Homogeneous Solution 2. 35		
	2.7.2 Particular Solution 2. 36		
	2.7.3 Zero-input and Zero-state Response 2. 36		
	2.7.4 Total Response 2. 37		
2.8	Classification of Continuous Time Systems	2. 43	
	2.8.1 Static and Dynamic Systems 2. 43		
	2.8.2 Time Invariant and Time Variant Systems 2. 43		
	2.8.3 Linear and Nonlinear Systems 2. 47		
	2.8.4 Causal and Noncausal Systems 2. 51		
	2.8.5 Stable and Unstable Systems 2. 54		
	2.8.6 Feedback and Nonfeedback Systems 2.59		
2.9	Convolution of Continuous Time Signals	2. 59	
	2.9.1 Response of LTI Continuous Time System using Convolution 2. 59		
	2.9.2 Properties of Convolution 2. 60		
	2.9.3 Interconnections of Continuous Time Systems 2. 62		
	2.9.4 Procedure to Perfom Convolution 2. 64		
	2.9.5 Unit Step Response using Convolution 2. 65		
2.10	Inverse System and Deconvolution	2. 76	
2.11	Summary of Important Concepts	2. 77	
2.12	Short Questions and Answers	2. 78	
2.13	MATLAB Programs	2. 84	
2.14	Exercises	2. 94	
	Chapter 3: Laplace Transform		
3.1	Introduction	3. 1	
3.2	Region of Convergence	3. 4	
3.3	Properties and Theorems of Laplace Transform	3. 18	
3.4	Poles and Zeros of Rational Function of s		
	3.4.1 Representation of Poles and Zeros in s-plane 3. 34		
	3.4.2 ROC of Rational Function of s 3. 35		
	3.4.3 Properties of ROC 3. 37		
3.5	Inverse Laplace Transform	3. 38	
	3.5.1 Inverse Laplace Transform by Partial Fraction Expansion Method 3. 39		
	3.5.2 Inverse Laplace Transform using Convolution Theorem 3. 44		
3.6	Analysis of LTI Continuous Time System using Laplace Transform		
	3.6.1 Transfer Function of LTI Continuous Time System 3.48		
	3.6.2 Impulse Response and Transfer Function 3. 48		
	3.6.3 Response of LTI Continuous Time System using Laplace Transform 3. 49		
	3.6.4 Convolution and Deconvolution using Laplace Transform 3. 50		
	3.6.5 Stability in s-Domain 3. 51		
3.7	Structures for Realization of LTI Continuous Time Systems in s-domain	3. 79	
	3.7.1 Direct Form-I Structure 3.80		

Contents ix

3.8 3.9 3.10 3.11	Summa Short (	Direct Form-II Structure 3. 81  Cascade Structure 3. 84  Parallel Structure 3. 85  ary of Important Concepts  Questions and Answers  AB Programs	3. 96 3. 97 3.101 3.107
C	napter	4: Fourier Series and Fourier Transform of Continuous Time Signature Signatu	gnais
4.1	Introdu		4. 1
4.2	_	ometric Form of Fourier Series	4. 1
	4.2.1	Definition of Trigonometric Form of Fourier Series 4. 1	
	4.2.2	Conditions for Existence of Fourier Series 4. 2	
	4.2.3	Derivation of Equations for $a_0$ , $a_n$ and $b_n$ 4. 2	
4.3		ential Form of Fourier Series	4. 5
	4.3.1	Definition of Exponential Form of Fourier Series 4. 5	
	4.3.2	Negative Frequency 4. 5	
	4.3.3	Derivation of Equation for c <sub>n</sub> 4. 6	
	4.3.4	Relation Between Fourier Coefficients of Trigonometric and Exponential Form 4. 6	
	4.3.5	Frequency Spectrum (or Line Spectrum) of Periodic Continuous Time Signals 4. 7	
4.4		Coefficients of Signals with Symmetry	4. 9
	4.4.1	Even Symmetry 4. 9	
	4.4.2		
	4.4.3 4.4.4	Half Wave Symmetry (or Alternation Symmetry) 4. 14  Quarter Wave Symmetry 4. 15	
4.5	Proper	ties of Fourier Series	4. 15
4.6	Dimini	shing of Fourier Coefficients	4. 17
4.7	Gibbs	Phenomenon	4. 18
4.8		Problems in Fourier Series	4. 19
4.9	Fourier	Transform	4. 41
	4.9.1	Development of Fourier Transform from Fourier Series 4. 41	
	4.9.2	Frequency Spectrum using Fourier Transform 4. 43	
4.10	Proper	ties of Fourier Transform	4. 44
4.11	Fourier	Transform of Some Important Signals	4. 53
4.12	Fourier	Transform of a Periodic Signal	4. 65
4.13	Analys	is of LTI Continuous Time System Using Fourier Transform	4. 65
	4.13.1	Transfer Function of LTI Continuous Time System in Frequency Domain 4. 65	
	4.13.2	Response of LTI Continuous Time System Using Fourier Transform 4. 67	
	4.13.3	Frequency Response of LTI Continuous Time System 4. 67	
4.14	Relatio	n Between Fourier and Laplace Transform	4. 69
4.15	Solved	Problems in Fourier Transform	4. 71
4.16	Summa	ary of Important Concepts	4. 80
4.17	Short Questions and Answers 4. 8		

x Contents

4.18	MATL	AB Programs	4. 88
4.19	Exercis	ses	4. 92
	•	Chapter 5: State Space Analysis of Continuous Time Systems	
5.1	Introdu	action	5. 1
5.2	State N	Model of a Continuous Time System	5. 1
5.3	State N	Model of a Continuous Time System from Direct Form-II Structure	5. 4
5.4	Transf	er Function of a Continuous Time System from State Model	5. 6
5.5	Solutio	on of State Equations and Response of Continuous Time System	5. 6
5.6	Solved	Problems in State Space Analysis	5. 8
5.7	Summ	ary of Important Concepts	5. 16
5.8		Questions and Answers	5. 16
5.9	MATL	AB Programs	5. 19
5.10	Exercis	ses	5. 20
		Chapter 6: Discrete Time Signals and Systems	
6.1	Discre	te and Digital Signals	6. 1
	6.1.1	Generation of Discrete Signals 6. 1	
	6.1.2	Representation of Discrete Time Signals 6. 2	
6.2	Standa	rd Discrete Time Signals	6. 3
6.3	Sampli	ing of Continuous Time (Analog) Signals	6. 6
	6.3.1	Sampling and Aliasing 6. 7	
6.4	Classif	ications of Discrete Time Signals	6. 10
	6.4.1	Deterministic and Nondeterministic Signals 6. 10	
	6.4.2	Periodic and Aperiodic Signals 6. 10	
	6.4.3	Symmetric (Even) and Antisymmetric (Odd) Signals 6. 12	
	6.4.4	Energy and Power Signals 6. 14	
	6.4.5	Causal, Noncausal and Anticausal Signals 6. 16	
6.5	Mathe	matical Operations on Discrete Time Signals	6. 17
	6.5.1	Scaling of Discrete Time Signals 6. 17	
	6.5.2	Folding (Reflection or Transpose) of Discrete Time Signals 6. 18	
	6.5.3	Time Shifting of Discrete Time Signals 6. 18	
	6.5.4	Addition of Discrete Time Signals 6. 19	
	6.5.5	Multiplication of Discrete Time Signals 6. 19	
6.6	Discre	te Time System	6. 20
	6.6.1	Mathematical Equation Governing Discrete Time System 6. 20	
	6.6.2	Block Diagram and Signal Flow Graph Representation of Discrete Time System 6. 22	
6.7	Respo	nse of LTI Discrete Time System in Time Domain	6. 25
	6.7.1	Zero-Input Response or Homogeneous Solution 6. 25	
	6.7.2	Particular Solution 6. 26	
	6.7.3	Zero-State Response 6. 27	
	6.7.4	Total Response 6. 27	

Contents	xi	

6.8	Classifications of Discrete Time Systems	6. 32
	6.8.1 Static and Dynamic Systems 6. 32	
	6.8.2 Time Invariant and Time Variant Systems 6. 32	
	6.8.3 Linear and Nonlinear Systems 6. 35	
	6.8.4 Causal and Noncausal Systems 6. 41	
	6.8.5 Stable and Unstable Systems 6. 43	
	6.8.6 FIR and IIR Systems 6. 45	
	6.8.7 Recursive and Nonrecursive Systems 6.45	
6.9	Discrete or Linear Convolution	6. 46
	6.9.1 Representation of Discrete Time Signal as Summation of Impulses 6. 47	
	6.9.2 Response of LTI Discrete Time System using Discrete Convolution 6. 48	
	6.9.3 Properties of Linear Convolution 6. 49	
	6.9.4 Interconnections of Discrete Time Systems 6.51	
	6.9.5 Methods of Performing Linear Convolution 6. 56	
6.10	Circular Convolution	6. 63
	6.10.1 Circular Representation and Circular Shift of Discrete Time Signal 6.63	
	6.10.2 Circular Symmetrics of Discrete Time Signal 6.65	
	6.10.3 Definition of Circular Convolution 6. 66	
	6.10.4 Procedure for Evaluating Circular Convolution 6. 67	
	6.10.5 Linear Convolution via Circular Convolution 6. 68	
	6.10.6 Methods of Computing Circular Convolution 6. 68	
6.11	Sectioned Convolution	6. 78
	6.11.1 Overlap Add Method 6. 78	
	6.11.2 Overlap Save Method 6. 79	
6.12	Inverse System and Deconvolution	6. 92
	6.12.1 Inverse System <i>6.92</i>	
	6.12.2 Deconvolution 6.93	
6.13	Correlation, Crosscorrelation and Autocorrelation	6. 95
	6.13.1 Procedure for Evaluating Correlation 6.96	
6.14	Circular Correlation	6.104
	6.14.1 Procedure for Evaluating Circular Correlation 6.105	
	6.14.2 Methods of Computing Circular Correlation 6.105	
6.15	Summary of Important Concepts	6.110
6.16	Short Questions and Answers	6.111
6.17	MATLAB Programs	6.115
6.18	Exercises	6.119
	Chapter 7: ₹ - Transform	
7.1	Introduction	7. 1
7.2	Region of Convergence	7. 3
7.3	Properties of <b>Z</b> -Transform	7. 11
7.4	Poles and Zeros of Rational Function of z	7. 27
	7.4.1 Representation of Poles and Zeros in z-plane 7. 28	

**xii** Contents

	7.4.2	ROC of Rational Function of z 7. 29	
	7.4.3	Properties of ROC 7. 30	
7.5	Inverse	e <b>Z</b> -Transform	7. 3
	7.5.1	Inverse <b>Z</b> -Transform by Contour Integration or Residue Method 7. 31	
	7.5.2	Inverse <b>Z</b> -Transform by Partial Fraction Expansion Method 7. 32	
	7.5.3	Inverse <b>Z</b> -Transform by Power Series Expansion Method 7. 35	
7.6	Analys	sis of LTI Discrete Time System Using Z-Transform	7. 47
	7.6.1	Transfer Function of LTI Discrete Time System 7. 47	
	7.6.2	Impulse Response and Transfer Function 7. 48	
	7.6.3	Response of LTI Discrete Time System Using <b>Z</b> -Transform 7. 49	
	7.6.4	Convolution and Deconvolution Using <b>₹</b> -Transform 7. 50	
	7.6.5	Stability in z-Domain 7. 51	
7.7	Relatio	on Between Laplace Transform and <b>Z</b> -Transform	7. 50
	7.7.1	Impulse Train Sampling of Continuous Time Signal 7. 56	
	7.7.2	Transformation from Laplace Transform to <b>Z</b> -Transform 7. 56	
	7.7.3	Relation Between s-Plane and z-Plane 7. 57	
7.8	Structu	res for Realization of LTI Discrete Time Systems in z-Domain	7. 59
7.9	Summ	ary of Important Concepts	7. 72
7.10	Short (	Questions and Answers	7. 73
7.11	MATL	AB Programs	7. 79
7.12	Exercis	ses	7. 84
	-	: Fourier Series and Fourier Transform of Discrete Time Signals	8. 1
8.1 8.2	Introduction Fourier Series of Discrete Time Signals (Discrete Time Fourier Series)		
0.2	8.2.1	Frequency Spectrum of Periodic Discrete Time Signals 8. 3	8. 1
	8.2.2	Properties of Discrete Time Fourier Series 8. 4	
8.3		r Transform of Discrete Time Signals (Discrete Time Fourier Transform)	8. 9
0.5	8.3.1	Development of Discrete Time Fourier Transform from Discrete Time Fourier Transform from Discrete Time Fourier Series 8. 9	0. )
	8.3.2	Definition of Discrete Time Fourier Transform 8. 10	
	8.3.3	Frequency Spectrum of Discrete Time Signal 8. 11	
	8.3.4	Inverse Discrete Time Fourier Transform 8. 11	
	8.3.5	Comparison of Fourier Transform of Discrete and Continuous Time Signals 8. 12	
8.4	Proper	ties of Discrete Time Fourier Transform	8. 12
8.5	-	te Time Fourier Transform of Periodic Discrete Time Signals	8. 20
8.6		sis of LTI Discrete Time System Using Discrete Time Fourier Transform	8. 22
	8.6.1	Transfer Function of LTI Discrete Time System in Frequency Domain 8. 22	
	8.6.2	Response of LTI Discrete Time System Using Discrete Time Fourier Transform 8. 23	
	8.6.3	Frequency Response of LTI Discrete Time System 8. 23	
	8.6.4	Frequency Response of First Order Discrete Time System 8. 25	
	8.6.5	Frequency Response of Second Order Discrete Time System 8. 31	

xiii
•

8.7	Aliasing in Frequency Spectrum Due to Sampling	8. 36
0.7	8.7.1 Signal Reconstruction (Recovery of Continuous Time Signal) 8. 38	0.50
	8.7.2 Sampling of Bandpass Signal 8.39	
8.8	Relation Between <b>Z</b> -Transform and Discrete Time Fourier Transform	8. 40
8.9	Summary of Important Concepts	8. 62
8.10	Short Questions and Answers	8. 63
8.11	MATLAB Programs	8. 68
8.12	Exercises	8. 73
Ch	napter 9: Discrete Fourier Transform (DFT) and Fast Fourier	Transform (FFT)
9.1	Introduction	9. 1
9.2	Discrete Fourier Transform (DFT) of Discrete Time Signal	9. 1
	9.2.1 Development of DFT from DTFT 9. 1	
	9.2.2 Definition of Discrete Fourier Transform (DFT) 9. 2	
	9.2.3 Frequency Spectrum Using DFT 9. 2	
	9.2.4 Inverse DFT <i>9. 3</i>	
9.3	Properties of DFT	9. 4
9.4	Relation Between DFT and Z-Transform	9. 10
9.5	Analysis of LTI Discrete Time Systems Using DFT	9. 10
9.6	Fast Fourier Transform (FFT)	9. 19
9.7	Decimation In Time (DIT) Radix-2 FFT	9. 21
	9.7.1 8-Point DFT Using Radix-2 DIT FFT 9. 23	
	9.7.2 Flow Graph for 8-Point DIT Radix-2 FFT 9. 27	
9.8	Decimation In Frequency (DIF) Radix-2 FFT	9. 29
	9.8.1 8-Point DFT Using Radix-2 DIF FFT 9. 32	
	9.8.2 Flow Graph for 8-Point DIF Radix-2 FFT 9. 34	
	9.8.3 Comparison of DIT and DIF Radix-2 FFT 9. 37	
9.9	Computation of Inverse DFT Using FFT	9. 37
9.10	Summary of Important Concepts	9. 56
9.11	Short Questions and Answers	9. 57
9.12	MATLAB Programs	9. 60
9.13	Exercises	9. 65
	Chapter 10: Structures for Realization of IIR and FIF	R Systems
10.1	Introduction	10. 1
10.2	Discrete Time IIR and FIR Systems	10. 1
	10.2.1 Discrete Time IIR System 10. 1	
	10.2.2 Discrete Time FIR System 10. 2	
10.3	Structures for Realization of IIR Systems	10. 3
	10.3.1 Direct Form-I Structure of IIR System 10. 4	
	10.3.2 Direct Form-II Structure of IIR System 10. 5	

**xiv** Contents

	10.3.3	Cascade Form Realization of IIR System 10. 8	
	10.3.4	Parallel Form Realization of IIR System 10. 8	
10.4	Struct	ures for Realization of FIR Systems	10. 29
	10.4.1	Direct Form Realization of FIR System 10. 30	
	10.4.2	Cascade Form Realization of FIR System 10. 30	
	10.4.3	Linear Phase Realization of FIR System 10. 31	
10.5	Summ	ary of Important Concepts	10. 37
10.6	Short	Questions and Answers	10.38
10.7	Exerci	ses	10.40
		<b>Chapter 11: State Space Analysis of Discrete Time Systems</b>	
11.1	T4 J		11 1
11.1	Introd		11. 1
11.2		Model of Discrete Time Systems	11. 1
11.3		Model of a Discrete Time System from Direct Form-II Structure	11. 4
11.4	Transf	er Function of a Discrete Time System from State Model	11. 5
11.5	Solution	on of State Equations and Response of Discrete Time System	11. 6
11.6	Solved	Problems in State Space Analysis of Discrete Time System	11. 8
11.7	Summ	ary of Important Concepts	11. 14
11.8	Short	Questions and Answers	11. 14
11.9	MATI	AB Programs	11. 17
11.10	Exerci	ses	11. 19
Appendix	1 .	Important Mathematical Relations	A. 1
Appendix	2 .	MATLAB Commands and Functions	A. 5
Appendix	3	Summary of Various Standard Transform Pairs	A. 11
Appendix	4	Summary of Properties of Various Transforms	A. 17
Index			I 1