

<b>Chapter 1 : Introduction to Control Systems 1-1 to 1-6</b>		2.10.3 Advantages of Analogous Systems .....2-16
1.1	Introduction..... 1-1	2.11 Representation by Nodal Method .....2-16
1.2	Important Definitions ..... 1-1	2.12 Solved Examples on Mathematical Modelling .....2-16
1.3	Open Loop System ..... 1-2	2.13 Thermal Systems .....2-20
1.3.1	Open Loop Examples..... 1-2	
1.3.2	Advantages and Disadvantages of Open Loop Systems..... 1-3	<b>Chapter 3 : Block Diagram Reduction 3-1 to 3-29</b>
1.4	Closed Loop System..... 1-3	3.1 Introduction ..... 3-1
1.4.1	Closed Loop Examples ..... 1-3	3.1.1 How to Draw a Block Diagram? ..... 3-1
1.4.2	Advantages and Disadvantages of Closed Loop System..... 1-5	3.2 Block Diagram Definitions..... 3-1
1.5	How does One Convert an Open Loop System to a Closed Loop System?..... 1-5	3.3 Block Diagram Reduction ..... 3-2
1.5.1	Comparison of Open and Closed Loop Systems ..... 1-6	3.3.1 Derivation of Closed Loop (Feedback) Transfer Function ..... 3-2
1.6	Requirements of a Good Control System ..... 1-6	3.3.2 Advantages of Block Diagram ..... 3-3
		3.3.3 Disadvantages of Block Diagram ..... 3-3
		3.4 Rules for Block Diagram Reduction ..... 3-3
		3.5 Solved Examples ..... 3-9
<b>Chapter 2 : Transfer Function and Mathematical Modelling 2-1 to 2-21</b>		<b>Chapter 4 : Signal Flow Graph 4-1 to 4-20</b>
2.1	Introduction..... 2-1	4.1 Introduction ..... 4-1
2.2	Transfer Function..... 2-1	4.1.1 How to Draw a Signal Flow Graph?..... 4-1
2.3	Poles and Zeros of a Transfer Function..... 2-4	4.2 Method to Draw SFG from System Equations ... 4-1
2.4	Properties of Transfer Function (T.F.) ..... 2-7	4.3 Method to Draw SFG from Block Diagrams ..... 4-3
2.5	Proper and Improper Transfer Functions ..... 2-7	4.4 Some Important Signal Flow Graph Terms ..... 4-4
2.6	Advantages and Disadvantages of Transfer Function..... 2-7	4.5 Properties of SFG ..... 4-4
2.7	Impulse Response..... 2-8	4.5.1 Comparison of Block Diagram and SFG Methods..... 4-4
2.7.1	Impulse Response of a System..... 2-8	4.6 Mason's Gain Formula ..... 4-5
2.8	Solved Examples on Transfer Functions..... 2-10	4.6.1 Mason's Gain Equation ..... 4-5
2.9	Mathematical Modelling of Mechanical and Electrical Systems ..... 2-11	4.7 Steps for Solving S.F.G. using Mason's Gain Formula..... 4-5
2.9.1	Translational Motion ..... 2-11	4.7.1 Solved Examples..... 4-6
2.9.2	Rotational Motion ..... 2-13	4.8 Solving SFG When Equations are Given .....4-19
2.9.3	Electrical Systems ..... 2-14	4.8.1 Solved Examples.....4-19
2.10	Analogous Systems ..... 2-14	4.9 Use of Mason's Gain Formula for Electrical Network .....4-19
2.10.1	Force - Voltage Analogy ..... 2-15	
2.10.2	Force - Current Analogy ..... 2-15	

**Chapter 5 : Time Response Analysis 5-1 to 5-43**

**5.1 Introduction..... 5-1**

5.1.1 Time Response ..... 5-1

**5.2 Inputs Supplied to a System..... 5-2**

**5.3 Steady State Response ..... 5-4**

5.3.1 Effect of Input R(s) on Steady State Error..... 5-5

5.3.2 Effect of Open Loop Transfer Function G(s) H(s) on Steady State Error  $e_{ss}$  ..... 5-7

**5.4 Subjecting a Type 0 System to a Step, Ramp and Parabolic Input..... 5-8**

5.4.1 Step Input to a Type 0 System..... 5-8

5.4.2 Ramp Input to a Type 0 System ..... 5-8

5.4.3 Parabolic Input to a Type 0 System..... 5-8

**5.5 Subjecting a Type 1 System to a Step, Ramp and Parabola Input..... 5-9**

5.5.1 Step Input to a Type 1 System..... 5-9

5.5.2 Ramp Input to a Type 1 System ..... 5-9

5.5.3 Parabolic Input to a Type 1 System..... 5-10

**5.6 Subjecting a Type 2 System to a Step, Ramp and Parabola Input..... 5-10**

5.6.1 Step Input to a Type 2 System..... 5-10

5.6.2 Ramp Input to Type 2 System ..... 5-11

5.6.3 Parabola Input to Type 2 System ..... 5-11

5.6.4 Examples on Steady State Response..... 5-12

**5.7 Transient Response ..... 5-18**

5.7.1 Analysis of First Order Systems ..... 5-18

5.7.2 Analysis of Second Order System..... 5-20

5.7.2(A) Damping Factor ..... 5-20

5.7.2(B) Natural Frequency of Oscillation ( $\omega_n$ ) ..... 5-20

5.7.2(C) Position of Poles in a 2<sup>nd</sup> Order System ..... 5-21

5.7.3 Effect of  $\xi$  on the Position of Closed Loop Poles..... 5-21

5.7.4 Unit Step Response of a 2<sup>nd</sup> Order System..... 5-22

5.7.5 Time Response of a Second Order System with  $0 < \xi < 1$  .....5-24

5.7.5(A) Derivation of Unit Impulse Response of a 2<sup>nd</sup> Order Underdamped System .....5-24

5.7.5(B) Derivation of Unit Step Response of a 2<sup>nd</sup> Order Underdamped System .....5-25

**5.8 Transient Response Specifications (Design Specifications for Second Order Systems) .....5-28**

5.8.1 Derivation of Rise Time ( $T_r$ ).....5-28

5.8.2 Derivation of Peak Time ( $T_p$ ).....5-29

5.8.3 Derivation of Peak Overshoot ( $M_p$ ) .....5-30

5.8.4 Derivation of Settling Time ( $T_s$ ) .....5-31

**5.9 Solved Examples on Transient Response.....5-32**

**5.10 Sensitivity.....5-42**

**Chapter 6 : Stability Analysis 6-1 to 6-19**

**6.1 Introduction ..... 6-1**

6.1.1 Stable System ..... 6-1

6.1.2 Unstable System ..... 6-1

6.1.3 Marginally Stable System ..... 6-2

**6.2 Time Response of Poles ..... 6-2**

**6.3 Hurwitz Stability Criterion ..... 6-6**

6.3.1 Disadvantages of the Hurwitz Criterion ..... 6-8

**6.4 Routh Stability Criterion ..... 6-8**

**6.5 Routh Criterion Special Cases.....6-11**

6.5.1 Special Case 1 .....6-11

6.5.2 Special Case 2.....6-13

**6.6 Relative Stability.....6-14**

**6.7 Application of Routh's Criterion.....6-15**

**6.8 Solved Examples .....6-15**

**Chapter 7 : Root Locus 7-1 to 7-42**

**7.1 Introduction ..... 7-1**

**7.2 Angle and Magnitude Condition ..... 7-2**

**7.3 Construction of Root Locus..... 7-3**

7.3.1 General Method for Drawing Root Locus..... 7-3

7.4	<b>Determining the Value of k from the Damping Ratio</b> ..... 7-8	<b>Chapter 9 : Bode Plots</b> ..... <b>9-1 to 9-48</b>
7.5	<b>Steps for Solving Problems on Root Locus</b> ..... 7-9	<b>9.1 Introduction</b> ..... 9-1
7.6	<b>Solved Examples</b> ..... 7-9	<b>9.2 Log-Scales</b> ..... 9-2
7.7	<b>Some Additional Important Points</b> ..... 7-40	9.2.1 Why do we Use the Log Scales on the X-axis? ..... 9-2
7.7.1	More Zeros and Less Poles ..... 7-40	9.2.2 What are Log-Scales? ..... 9-2
7.7.2	Value of Gain Margin ..... 7-40	9.2.3 Scale Marking..... 9-3
7.7.3	Phase Margin from Root Locus..... 7-41	<b>9.3 Standard Form for GH (j<math>\omega</math>)</b> ..... <b>9-3</b>
7.8	<b>Effect of Addition of Poles and Zeros on Root Locus</b> ..... 7-41	<b>9.4 Bode Plots of Standard Factors</b> ..... <b>9-4</b>
7.8.1	Effect of Addition of Poles - Dominant Poles..... 7-41	9.4.1 Bode Gain Factor $K_1$ ..... 9-4
7.8.2	Effect of Addition of Zeros ..... 7-41	9.4.2 Poles at Origin or Integral Factor $\left(\frac{1}{j\omega}\right)^k$ ..... 9-4
<b>Chapter 8 : Frequency Response Analysis 8-1 to 8-15</b>		9.4.3 Zeros at Origin or Derivative Factor $(j\omega)^g$ ..... 9-6
8.1	<b>Introduction</b> ..... <b>8-1</b>	9.4.4 First Order Poles $\frac{1}{\left(1 + j\frac{\omega}{P_1}\right)}$ ..... 9-6
8.2	<b>Frequency Response</b> ..... <b>8-2</b>	9.4.5 First Order Zeros $\left(1 + j\frac{\omega}{Z_1}\right)$ ..... 9-8
8.2.1	Sinusoidal Response of a Linear System..... 8-2	9.4.6 Second Order Poles ..... 9-8
8.2.2	Methods Used in Frequency Response..... 8-3	9.4.7 Second Order Zeros.....9-10
8.2.3	Advantages of Frequency Response Analysis ..... 8-3	<b>9.5 Frequency Domain Specifications</b> ..... <b>9-11</b>
8.2.4	Time Response and Frequency Response Analysis ..... 8-3	9.5.1 Gain Margin (G.M.).....9-11
8.2.5	Disadvantages of Frequency Response Methods..... 8-4	9.5.2 Phase Margin ( $\phi_{pm}$ ).....9-11
8.3	<b>Transfer Function and Frequency Response</b> .... <b>8-4</b>	9.5.3 Bandwidth .....9-11
8.3.1	Transfer Function and Frequency Response of a R - C Circuit ..... 8-4	9.5.4 Cut-off Frequency ( $\omega_c$ ).....9-12
8.4	<b>Frequency Response Specifications</b> ..... <b>8-6</b>	9.5.5 Cut-off Rate .....9-12
8.5	<b>Co-relation between Time and Frequency Domain</b> ..... <b>8-6</b>	9.5.6 Resonance Peak Frequency ( $M_p$ ).....9-12
8.5.1	Derivation of $\omega_r$ and $M_r$ ..... 8-6	9.5.7 Resonant Frequency ( $\omega_p$ ).....9-12
8.5.2	Relationship between Frequency Response Specifications and Time Response Specifications..... 8-7	9.5.8 Gain Crossover Frequency ( $\omega_{gc}$ ) .....9-12
8.6	<b>Bandwidth</b> ..... <b>8-8</b>	9.5.9 Phase Margin Angle ( $\gamma$ ) .....9-12
8.7	<b>Solved Examples</b> ..... <b>8-9</b>	9.5.10 Phase Crossover Frequency ( $\omega_{pc}$ ) .....9-12
		<b>9.6 Relative Stability</b> ..... <b>9-12</b>
		<b>9.7 Steps for Solving Bode Plots</b> ..... <b>9-13</b>
		<b>9.8 Summary of Bode Magnitude and Phase Plots of Various Terms</b> ..... <b>9-14</b>

9.9	How to Draw Lines of 20, 40, 60 dB/dec.....	9-14	11.8	Lag - Lead Compensator.....	11-8
9.10	Advantages of Bode Plots.....	9-16	11.9	Design of Compensators using Bode Plot.....	11-8
9.11	Solved Examples.....	9-16	11.9.1	Bode Plot of Lead Compensator.....	11-9
9.12	Other Terms in Bode Plots.....	9-46	11.9.1(A)	Derivation of Maximum Phase-Lead Frequency ( $\omega_m$ ).....	11-9
9.12.1	Bode Plot for Transportation Lag.....	9-46	11.9.1(B)	Derivation of Maximum Phase Lead Angle ( $\phi_m$ ).....	11-10
<b>Chapter 10 : Polar and Nyquist Plots</b>			<b>10-1 to 10-32</b>		
10.1	Introduction.....	10-1	11.9.2	Steps to Design Lead Compensator.....	11-10
10.2	Polar Plots.....	10-1	11.9.3	Design of Lag Compensator using Bode Plot.....	11-17
10.2.1	Advantages of Polar Plots.....	10-1	11.9.4	Steps to Design a Lag Compensator.....	11-18
10.2.2	Polar Plot of a 1 <sup>st</sup> Order Pole ( $\frac{1}{s+p}$ ).....	10-2	11.9.5	Bode Plot of Lag-Lead Compensator.....	11-22
10.3	Effect of Adding More Simple Poles.....	10-3	11.10	Compensation using Root Locus.....	11-25
10.4	Effect of Adding Pole at Origin.....	10-5	11.10.1	Lead Compensator Design using Root Locus.....	11-26
10.5	Stability on Polar Plots.....	10-8	11.10.2	Designing a Lag Compensator using Root Locus.....	11-28
10.5.1	A Simple Way to Check Stability on Polar Plots.....	10-11	11.10.3	Designing Lag-Lead Compensator using Root Locus.....	11-31
10.6	Nyquist Analysis - Mapping.....	10-12	11.10.4	Effects and Characteristics of Phase Lead and Phase Lag Compensation Network.....	11-35
10.7	Nyquist Stability Criterion.....	10-14	<b>Chapter 12 : State Space Analysis</b>		
10.7.1	Actual Encirclement.....	10-15	<b>12-1 to 12-34</b>		
10.7.2	Modified Nyquist Contour.....	10-15	12.1	Introduction.....	12-1
10.7.3	Advantages of Nyquist Plot.....	10-16	12.2	Difference between State Space Analysis and Transfer Function.....	12-1
10.8	Relative Stability.....	10-16	12.3	Advantages and Disadvantages of Conventional Control Theory.....	12-1
10.9	Solved Examples.....	10-16	12.4	Advantages and Disadvantages of Modern Control Theory.....	12-1
<b>Chapter 11 : Introduction to Compensator Design</b>			<b>11-1 to 11-35</b>		
11.1	Introduction.....	11-1	12.5	Concepts of State, State Variables and State Model.....	12-2
11.2	Series Compensation.....	11-2	12.5.1	Definition of State and State Variables, State Vectors and State Space.....	12-2
11.3	Gain Adjustment.....	11-2			
11.4	Standard Compensators.....	11-4			
11.5	Lead Compensator.....	11-4			
11.6	Lag Compensators.....	11-6			
11.7	Difference between Phase Lead and Lag Compensation.....	11-7			

<p><b>12.6 State Variable Representation of Control System ..... 12-3</b></p> <p>12.6.1 State Model of Linear Systems..... 12-5</p> <p><b>12.7 State Diagram Representation ..... 12-6</b></p> <p>12.7.1 Non-uniqueness of the State Variable..... 12-6</p> <p><b>12.8 State Space Representation by Specific Types of State Variables ..... 12-7</b></p> <p>12.8.1 Different Representation of State Model..... 12-7</p> <p>12.8.2 Forming State Models by Physical Variables..... 12-7</p> <p>12.8.3 Forming State Model by Phase Variables .....12-10</p> <p>12.8.4 State Space Representation using Phase Variable in Observable Controllable Form .....12-11</p> <p>12.8.5 Explanation of State Variable Model by Phase Variables using Differential Equation .....12-12</p> <p><b>12.9 To Obtain Transfer Function from State Variable Model and Vice Versa.....12-13</b></p> <p>12.9.1 To Obtain State Variable Form from Transfer Function.....12-16</p> <p>12.9.2 Canonical Form of State Variable Model.....12-17</p> <p><b>12.10 Diagonalisation.....12-19</b></p> <p>12.10.1 Eigen Values and Eigen Vectors .....12-19</p>	<p>12.10.2 To Obtain Model Matrix.....12-20</p> <p><b>12.11 Equivalent State Equations ..... 12-21</b></p> <p><b>12.12 Solution of LTI State Equations ..... 12-22</b></p> <p>12.12.1 Solution of Homogeneous State Equation.....12-22</p> <p>12.12.2 Properties of State Transition Matrix .....12-23</p> <p>12.12.3 Solution of Non-homogeneous State Equation.....12-24</p> <p>12.12.4 Another Way of Solution of LTI State Equations.....12-25</p> <p>12.12.4(A) Solution in Time Domain .....12-25</p> <p>12.12.5 Properties of State Transition Method .....12-25</p> <p>12.12.6 Solution using Laplace Transform .....12-26</p> <p>12.12.7 Controllability and Observability .....12-26</p> <p>12.12.8 Transformations.....12-30</p> <p>12.12.9 Transformation to Observable Canonical form CCF .....12-31</p> <p>12.12.10 Another way of Computation by Canonical Transformation .....12-31</p> <p><b>12.13 Ackerman’s Formula ..... 12-33</b></p>
--	--