

CONTENTS

PREFACE

xvii

FOREWORD

xxi

1 INTRODUCTION TO CONTROL SYSTEMS

1

- 1-1 Introduction 1
- 1-2 Definition of a Control System 2
- 1-3 Types of Control Systems 3
 - Closed-Loop and Open-Loop Control Systems, 3*
 - Analog and Digital Control Systems, 5*
 - Linear and Nonlinear Control Systems, 5*
 - Classification of Control Systems According to Application, 6*
- 1-4 Characteristics of Control Systems 10
 - Stability, 10*
 - Accuracy, 11*
 - Speed of Response, 12*
 - Sensitivity, 12*



1-5	Representing a Control System	12
-----	-------------------------------	----

Block Diagram, 13

Signal Flow Graph, 14

1-6	Terms and Conventions	14
-----	-----------------------	----

Summary 20

Questions 20

2 CONTROL SYSTEM COMPONENTS

22

2-1	Introduction	22
-----	--------------	----

2-2	Temperature Sensors	23
-----	---------------------	----

Thermistor, 23

Resistive Sensor, 25

Thermocouple, 26

IC Temperature Sensor, 28

2-3	Strain Gage	29
-----	-------------	----

2-4	Phototransistor	35
-----	-----------------	----

2-5	Photoconductive Cell	46
-----	----------------------	----

2-6	Optocoupler	47
-----	-------------	----

2-7	Optointerrupter Device	51
-----	------------------------	----

2-8	Hall Effect Device	55
-----	--------------------	----

2-9	Digital-to-Analog Converter	59
-----	-----------------------------	----

2-10	Analog-to-Digital Converters	65
------	------------------------------	----

Simultaneous ADC, 65

Monotonic ADC, 66

Tracking ADC, 68

Single-Slope ADC, 68

Dual-Slope ADC, 71

Successive Approximation ADC, 73

2-11	Voltage-to-Frequency and Frequency-to-Voltage Converters	78
------	--	----

2-12	Shaft Position Encoder	83
------	------------------------	----

2-13	Solenoid	88
------	----------	----

2-14	Gears	90
------	-------	----

2-15	Linear Variable Differential Transformer	95
------	--	----

2-16	Accelerometer	96
------	---------------	----

2-17	Potentiometer	101
------	---------------	-----

Summary 104

Questions 105

Problems	106
Lab Experiment 2-1 Optical Sensing of Motor Speed	108
Lab Experiment 2-2 Optical Sensing of Angular Position	109

3 MOTORS

112

3-1	Introduction	112
3-2	DC Generator	113
3-3	DC Motor	120
	<i>Motor Speed-Torque Characteristics,</i>	<i>129</i>
	<i>Motor Models,</i>	<i>132</i>
	<i>Stepper Motors,</i>	<i>137</i>
3-4	Permanent-Magnet Stepper Motor	139
3-5	Single-Stack Variable-Reluctance Stepper Motor	140
3-6	Multistack Variable-Reluctance Stepper Motor	144
3-7	Hybrid Stepper Motor	148
3-8	Static Torque Characteristics of the Stepper Motor	154
3-9	Dynamic Torque Characteristics of the Stepper Motor	156
3-10	Mechanical Resonance	161
3-11	Programmable Sequencer Design	163
3-12	Stepper Motor Drivers	166
	<i>Bilevel Drive,</i>	<i>170</i>
	<i>Chopper Drive,</i>	<i>171</i>
3-13	Practical Stepper Motor Motion Control System	172
	Summary	176
	Questions	178
	Problems	178
	Lab Experiment 3-1 Speed-Torque Characteristics of a DC PM Motor	180
	Lab Experiment 3-2 Transfer Function of a DC PM Motor	182
	Lab Experiment 3-3 Stepper Motor Motion Control	186

4 REPRESENTING CONTROL SYSTEMS

190

4-1	Introduction	190
4-2	Laplace Transform	191

4-3	Transfer Function	193
4-4	Block Diagrams	193
4-5	Block Diagram Classification	194
4-6	Types of Blocks	195
	<i>Proportional Block</i> ,	196
	<i>Integration Block</i> ,	197
	<i>Proportional plus Integration Block</i> ,	198
	<i>Derivative Block</i> ,	200
	<i>Proportional plus Derivative Block</i> ,	201
	<i>Simple Phase-Lag Block</i> ,	203
	<i>Simple Phase-Lead Block</i> ,	204
	<i>Quadratic Block</i> ,	206
	<i>Combination Block</i> ,	208
4-7	Block Diagram Simplification Methods	209
	<i>Cascaded or Series Summing Junctions</i> ,	209
	<i>Cascaded Blocks</i> ,	210
	<i>Parallel Blocks</i> ,	210
	<i>Moving a Takeoff Point</i> ,	211
	<i>Moving a Summing Junction</i> ,	212
	<i>Transfer Function of a Standard Closed-Loop Block Diagram</i> ,	213
4-8	Signal Flow Graph	216
	<i>Definitions of Some Important Terms</i> ,	216
	<i>Signal Flow Graph Construction</i> ,	217
	<i>Transfer Function Determination of a Signal Flow Graph</i> ,	218
4-9	Block Diagram versus Signal Flow Graph	223
	Summary	223
	Questions	224
	Problems	224

5 FEEDBACK SYSTEM CHARACTERISTICS AND ANALYSIS

229

5-1	Introduction	229
5-2	Open-Loop and Closed-Loop Systems	231
5-3	System Accuracy	235
	<i>Type 0 System ($j = 0$)</i> ,	237
	<i>Type 1 System ($j = 1$)</i> ,	238
	<i>Type 2 System ($j = 2$)</i> ,	239
5-4	System Sensitivity	242
5-5	Effect of Disturbances	247

5-6	Effect of Feedback on System Transient Response	249
5-7	PLL Control System	250
5-8	Stability	251
	<i>Bode Diagram</i> ,	258
	<i>Nyquist Diagram</i> ,	261
	<i>Routh-Hurwitz Method</i> ,	264
	Summary	269
	Questions	271
	Problems	272
	Lab Experiment 5-1 Open-Loop System	277
	Lab Experiment 5-2 Closed-Loop System	279

6 TIME-DOMAIN ANALYSIS

283

6-1	Introduction	283
6-2	Test Signals	284
6-3	Poles and Zeros	286
6-4	First-Order-System Models	287
6-5	First-Order-System Step Response	288
6-6	Second-Order-System Models	293
6-7	Second-Order-System Step Response	295
	<i>Underdamped System Step Response</i> ,	296
	<i>Critically-Damped-System Step Response</i> ,	303
	<i>Overdamped-System Step Response</i> ,	304
6-8	Second-Order-System Ramp Response	310
	<i>Underdamped-System Ramp Response</i> ,	310
	<i>Critically-Damped-System Ramp Response</i> ,	313
	<i>Overdamped-System Ramp Response</i> ,	313
6-9	The Relationship between the Poles and Zeros in the S -plane and the corresponding Responses in the Time and Frequency Domains	315
	<i>Single-Pole System</i> ,	316
	<i>Single-Pole, Single-Zero System</i> ,	317
	<i>Second-Order System</i> ,	322
	Summary	339
	Questions	340
	Problems	341
	Lab Experiment 6-1 Second-Order System	344

- 7-1 Introduction 348
- 7-2 Polar Plot 350
- 7-3 Bode Plots 352
- 7-4 Concepts of Bode Plots 352
- 7-5 Constructing Bode Plots 356
 - Bode Plots of a Constant $\pm K$, 356*
 - Bode Plots of Pole-Zero at the Origin of the S Plane: $(s^{\pm 1})$, 359*
 - Bode Plots of Finite Zero or Pole: $(s\tau + 1)^{\pm 1}$, 364*
 - Bode Plots for a Quadratic $[s^2 + 2\zeta\omega_n s + \omega_n^2]^{\pm 1}$, 369*
- 7-6 Steps for Plotting Bode Plots 378
- 7-7 Stability Analysis Using Bode Plots 379
 - Gain Margin, 379*
 - Phase Margin, 380*
- 7-8 System Analysis Using Bode Plots 380
 - K_{max} for a Marginally Stable System, 383*
 - K for a Desired Phase Margin, 385*
 - Effect of Delay on System Stability, 386*
- 7-9 Time-Domain versus Frequency-Domain Analysis 390
 - Summary 390
 - Questions 391
 - Problems 391
 - Lab Experiment 7-1 Frequency Response of a First-Order Low-Pass Filter 396
 - Lab Experience 7-2 Frequency Response of a Peaking Amplifier 398

8 ANALOG CONTROL SYSTEMS

- 8-1 Introduction 402
- 8-2 Speed Control System 403
- 8-3 Position Control System 406
 - System Models, 410*
 - System Transient Response to Step and Ramp Inputs, 411*
 - Derivative Feedback, 417*
 - Adaptive Position Control, 420*
 - System Dynamics, 423*

8-4	Practical Servomechanism Systems	429
	<i>Speed Control System, 429</i>	
	<i>Position Control System, 434</i>	
8-5	Temperature Control System	435
	<i>System Models, 437</i>	
8-6	Liquid-Level Control System	440
	<i>System Models, 442</i>	
	<i>Electromechanical Liquid-Level Control System, 444</i>	
8-7	Performance Characteristics of First-Order Systems	449
	<i>Accuracy, 451</i>	
	<i>Sensitivity, 451</i>	
	<i>Disturbance Rejection, 451</i>	
	<i>Step Response, 452</i>	
	<i>General Remarks, 452</i>	
	<i>DC Motor Dynamics, 453</i>	
	Summary	456
	Questions	457
	Problems	458
	Lab Experiment 8-1 Open-Loop Speed Control System	462
	Lab Experiment 8-2 Closed-Loop Speed Control System	464
	Lab Experiment 8-3 Position Control System	466

9 DIGITAL CONTROL SYSTEMS

469

9-1	Introduction	469
9-2	Digital Temperature Control System	469
	<i>System Specifications, 470</i>	
	<i>Block Diagram, 470</i>	
	<i>System Design, 470</i>	
	<i>Schematic Diagram, 481</i>	
9-3	Digital DC Motor Speed Control System	483
	<i>System Specifications, 483</i>	
	<i>Block Diagram, 483</i>	
	<i>System Design, 484</i>	
	<i>Schematic Diagram, 496</i>	
9-4	Stepper Motor Position Control System	497
	<i>System Specifications, 497</i>	
	<i>Block Diagram, 498</i>	

- System Design*, 498
 - Schematic Diagram*, 511
- 9-5 Appliance Timer 511
 - System Specifications*, 512
 - Block Diagram*, 512
 - System Design*, 512
 - Schematic Diagram*, 517
- 9-6 Digital Light-Intensity Controller 518
 - System Specifications*, 519
 - Block Diagram*, 519
 - System Design*, 520
 - Schematic Diagram*, 524
- 9-7 Analog versus Digital Control Systems 525
 - Summary 526
 - Questions 526
 - Problems 527
 - Lab Experiment 9-1 Stepper Motor Translator/Driver and Drive Circuit 527
 - Lab Experiment 9-2 Digital Light-Intensity Controller 534

10 MICROPROCESSOR-BASED CONTROL SYSTEMS

538

- 10-1 Introduction 538
- 10-2 Microprocessor-Controlled Home Heating and Cooling System 538
 - Block Diagram*, 539
 - System Description*, 539
 - System Specifications*, 540
 - System Design*, 541
 - System Hardware*, 541
 - System Software*, 547
- 10-3 Microprocessor-Based DC Motor Speed Control System 551
 - Block Diagram*, 551
 - System Description*, 551
 - System Specifications*, 552
 - System Design*, 553
 - System Hardware*, 553
 - System Software*, 556
- 10-4 Microprocessor-Controlled Appliance Timer 559
 - Block Diagram*, 559
 - System Description*, 559

	<i>System Specifications, 562</i>	
	<i>System Design, 562</i>	
	<i>System Hardware, 562</i>	
	<i>System Software, 568</i>	
10–5	Microprocessor-Based Light-Intensity Controller	569
	<i>Block Diagram, 570</i>	
	<i>System Description, 570</i>	
	<i>System Specifications, 571</i>	
	<i>System Design, 571</i>	
	<i>System Hardware, 571</i>	
	<i>System Software, 575</i>	
	Summary	577
	Questions	577
	Problems	578
	Lab Experiment 10–1 Microprocessor-Based Temperature Control System	578
	Lab Experiment 10–2 Microprocessor-Based Light-Intensity Controller	581

APPENDIX A	STEP RESPONSE OF A FIRST-ORDER SYSTEM	586
APPENDIX B	HYDRAULIC SYSTEM	589
APPENDIX C	DATA SPECS	593
APPENDIX D	ANSWERS TO ODD-NUMBERED PROBLEMS	642
INDEX		651