

# Contents

<b>Preface</b>	<b>ix</b>
<b>1 Introduction to Feedback Control</b>	<b>1</b>
1.1 Introduction	1
1.2 Historical Background	3
1.3 Structure of the Book	4
1.4 A Survival Guide to MATLAB	6
1.4.1 A Brief Overview of MATLAB	6
1.4.2 Standard MATLAB Statements and Functions	6
1.4.3 Graphics Facilities in MATLAB	7
1.4.4 On-Line Help Facilities in MATLAB	8
1.4.5 MATLAB Toolboxes	8
Problems	9
<b>2 Mathematical Models of Feedback Control Systems</b>	<b>11</b>
2.1 A Physical Modeling Example	11
2.2 The Laplace Transformation	12
2.3 Transfer Function Models	14
2.3.1 Transfer Functions of Control Systems	14
2.3.2 MATLAB Representations of Transfer Functions	14
2.3.3 Transfer Function Matrices for Multivariable Systems	16
2.3.4 Transfer Functions of Discrete-Time Systems	16
2.4 Other Mathematical Model Representations	17
2.4.1 State Space Modeling	17
2.4.2 Zero-Pole-Gain Description	19
2.5 Modeling of Interconnected Block Diagrams	20
2.5.1 Series Connection	20
2.5.2 Parallel Connection	20
2.5.3 Feedback Connection	21
2.5.4 More Complicated Connections	22
2.6 Conversion Between Different Model Objects	24
2.6.1 Conversion to Transfer Functions	25
2.6.2 Conversion to Zero-Pole-Gain Models	26
2.6.3 State Space Realization	27

---

2.6.4	Conversion Between Continuous and Discrete-Time Models . . . . .	34
2.7	An Introduction to System Identification . . . . .	35
2.7.1	Identification of Discrete-Time Systems . . . . .	35
2.7.2	Order Selections . . . . .	40
2.7.3	Generation of Identification Signals . . . . .	41
2.7.4	Identification of Multivariable Systems . . . . .	44
Problems	. . . . .	45
<b>3</b>	<b>Analysis of Linear Control Systems</b>	<b>51</b>
3.1	Properties of Linear Control Systems . . . . .	52
3.1.1	Stability Analysis . . . . .	52
3.1.2	Controllability and Observability Analysis . . . . .	55
3.1.3	Kalman Decomposition of Linear Systems . . . . .	59
3.1.4	Time Moments and Markov Parameters . . . . .	62
3.1.5	Norm Measures of Signals and Systems . . . . .	64
3.2	Time Domain Analysis of Linear Systems . . . . .	66
3.2.1	Analytical Solutions to Linear Time Responses . . . . .	66
3.2.2	Analytical Solutions to Discrete-Time Systems . . . . .	69
3.3	Numerical Simulation of Linear Systems . . . . .	70
3.3.1	Step Responses of Linear Systems . . . . .	70
3.3.2	Impulse Responses of Linear Systems . . . . .	75
3.3.3	Time Responses to Arbitrary Inputs . . . . .	76
3.4	Root Locus of Linear Systems . . . . .	78
3.5	Frequency Domain Analysis of Linear Systems . . . . .	84
3.5.1	Frequency Domain Graphs with MATLAB . . . . .	84
3.5.2	Stability Analysis Using Frequency Domain Methods . . . . .	87
3.5.3	Gain and Phase Margins of a System . . . . .	88
3.5.4	Variations of Conventional Nyquist Plots . . . . .	90
3.6	Introduction to Model Reduction Techniques . . . . .	92
3.6.1	Padé Approximations and Routh Approximations . . . . .	92
3.6.2	Padé Approximations to Delay Terms . . . . .	95
3.6.3	Suboptimal Reduction Techniques for Systems with Delays . . . . .	98
3.6.4	State Space Model Reduction . . . . .	101
Problems	. . . . .	103
<b>4</b>	<b>Simulation Analysis of Nonlinear Systems</b>	<b>111</b>
4.1	An Introduction to Simulink . . . . .	111
4.1.1	Commonly Used Simulink Blocks . . . . .	112
4.1.2	Simulink Modeling . . . . .	115
4.1.3	Simulation Algorithms and Control Parameters . . . . .	116
4.2	Modeling of Nonlinear Systems by Examples . . . . .	118
4.3	Nonlinear Elements Modeling . . . . .	126
4.3.1	Modeling of Piecewise Linear Nonlinearities . . . . .	126
4.3.2	Limit Cycles of Nonlinear Systems . . . . .	130
4.4	Linearization of Nonlinear Models . . . . .	131
Problems	. . . . .	135

<b>5</b>	<b>Model-Based Controller Design</b>	<b>141</b>
5.1	Cascade Lead-Lag Compensator Design	142
5.1.1	Introduction to Lead-Lag Synthesis	142
5.1.2	Lead-Lag Synthesis by Phase Margin Assignment	148
5.2	Linear Quadratic Optimal Control	153
5.2.1	Linear Quadratic Optimal Control Strategies	153
5.2.2	Linear Quadratic Regulator Problems	154
5.2.3	Linear Quadratic Control for Discrete-Time Systems	157
5.2.4	Selection of Weighting Matrices	158
5.2.5	Observers and Observer Design	161
5.2.6	State Feedback and Observer-Based Controllers	164
5.3	Pole Placement Design	167
5.3.1	The Bass–Gura Algorithm	168
5.3.2	Ackermann’s Algorithm	169
5.3.3	Numerically Robust Pole Placement Algorithm	169
5.3.4	Observer Design Using the Pole Placement Technique	171
5.3.5	Observer-Based Controller Design Using the Pole Placement Technique	171
5.4	Decoupling Control of Multivariable Systems	173
5.4.1	Decoupling Control with State Feedback	173
5.4.2	Pole Placement of Decoupling Systems with State Feedback	175
5.5	SISOTool: An Interactive Controller Design Tool	177
	Problems	180
<b>6</b>	<b>PID Controller Design</b>	<b>183</b>
6.1	Introduction	184
6.1.1	The PID Actions	184
6.1.2	PID Control with Derivative in the Feedback Loop	186
6.2	Ziegler–Nichols Tuning Formula	187
6.2.1	Empirical Ziegler–Nichols Tuning Formula	187
6.2.2	Derivative Action in the Feedback Path	191
6.2.3	Methods for First-Order Plus Dead Time Model Fitting	193
6.2.4	A Modified Ziegler–Nichols Formula	196
6.3	Other PID Controller Tuning Formulae	199
6.3.1	Chien–Hrones–Reswick PID Tuning Algorithm	199
6.3.2	Cohen–Coon Tuning Algorithm	200
6.3.3	Refined Ziegler–Nichols Tuning	202
6.3.4	The Wang–Juang–Chan Tuning Formula	205
6.3.5	Optimum PID Controller Design	205
6.4	PID Controller Tuning Algorithms for Other Types of Plants	212
6.4.1	PD and PID Parameter Setting for IPDT Models	212
6.4.2	PD and PID Parameters for FOIPDT Models	213
6.4.3	PID Parameter Settings for Unstable FOPDT Models	215
6.5	PID_Tuner: A PID Controller Design Program for FOPDT Models	215
6.6	Optimal Controller Design	218
6.6.1	Solutions to Optimization Problems with MATLAB	218

---

6.6.2	Optimal Controller Design . . . . .	220
6.6.3	A MATLAB/Simulink-Based Optimal Controller Designer and Its Applications . . . . .	223
6.7	More Topics on PID Control . . . . .	227
6.7.1	Integral Windup and Anti-Windup PID Controllers . . . . .	227
6.7.2	Automatic Tuning of PID Controllers . . . . .	229
6.7.3	Control Strategy Selections . . . . .	232
	Problems . . . . .	233
<b>7</b>	<b>Robust Control Systems Design</b>	<b>237</b>
7.1	Linear Quadratic Gaussian Control . . . . .	238
7.1.1	LQG Problem . . . . .	238
7.1.2	LQG Problem Solutions Using MATLAB . . . . .	238
7.1.3	LQG with Loop Transfer Recovery . . . . .	243
7.2	General Descriptions of the Robust Control Problems . . . . .	249
7.2.1	Small Gain Theorem . . . . .	250
7.2.2	Unstructured Uncertainties . . . . .	250
7.2.3	Robust Control Problems . . . . .	251
7.2.4	Model Representation Under MATLAB . . . . .	252
7.2.5	Dealing with Poles on an Imaginary Axis . . . . .	253
7.3	$\mathcal{H}_\infty$ Controller Design . . . . .	255
7.3.1	Augmentations of the Model with Weighting Functions . . . . .	255
7.3.2	Model Augmentation with Weighting Function Under MATLAB . . . . .	257
7.3.3	Weighted Sensitivity Problems: A Simple Case . . . . .	258
7.3.4	$\mathcal{H}_\infty$ Controller Design: The General Case . . . . .	264
7.3.5	Optimal $\mathcal{H}_\infty$ Controller Design . . . . .	269
7.4	Optimal $\mathcal{H}_2$ Controller Design . . . . .	273
7.5	The Effects of Weighting Functions in $\mathcal{H}_\infty$ Control . . . . .	275
	Problems . . . . .	283
<b>8</b>	<b>Fractional-Order Controller: An Introduction</b>	<b>285</b>
8.1	Fractional-Order Calculus and Its Computations . . . . .	286
8.1.1	Definitions of Fractional-Order Calculus . . . . .	287
8.1.2	Properties of Fractional-Order Differentiations . . . . .	288
8.2	Frequency and Time Domain Analysis of Fractional-Order Linear Systems . . . . .	289
8.2.1	Fractional-Order Transfer Function Modeling . . . . .	289
8.2.2	Interconnections of Fractional-Order Blocks . . . . .	290
8.2.3	Frequency Domain Analysis of Linear Fractional-Order Systems . . . . .	291
8.2.4	Time Domain Analysis of Fractional-Order Systems . . . . .	292
8.3	Filter Approximation to Fractional-Order Differentiations . . . . .	294
8.3.1	Oustaloup's Recursive Filter . . . . .	294
8.3.2	A Refined Oustaloup Filter . . . . .	296
8.3.3	Simulink-Based Fractional-Order Nonlinear Differential Equation Solutions . . . . .	298
8.4	Model Reduction Techniques for Fractional-Order Systems . . . . .	300
8.5	Controller Design Studies for Fractional-Order Systems . . . . .	302

Problems . . . . . 306

**Appendix**

**CtrlLAB: A Feedback Control System Analysis and Design Tool** **309**

A.1 Introduction . . . . . 309

    A.1.1 What Is CtrlLAB? . . . . . 309

    A.1.2 Installation and Requirements . . . . . 310

    A.1.3 Execution of CtrlLAB . . . . . 310

    A.1.4 Copyright and Declaration of CtrlLAB . . . . . 311

A.2 Model Entry and Model Conversion . . . . . 311

    A.2.1 Transfer Function Entry . . . . . 311

    A.2.2 Entering Other Model Representations . . . . . 311

    A.2.3 A More Complicated Model Entry . . . . . 312

A.3 Model Transformation and Reduction . . . . . 314

    A.3.1 Model Display . . . . . 314

    A.3.2 State Space Realizations . . . . . 316

    A.3.3 Model Reduction . . . . . 316

A.4 Feedback Control System Analysis . . . . . 318

    A.4.1 Frequency Domain Analysis . . . . . 319

    A.4.2 Time Domain Analysis . . . . . 320

    A.4.3 System Properties Analysis . . . . . 323

A.5 Controller Design Examples . . . . . 324

    A.5.1 Model-Based Controller Designs . . . . . 324

    A.5.2 Design of PID Controllers . . . . . 325

    A.5.3 Robust Controller Design . . . . . 326

A.6 Graphical Interface-Based Tools . . . . . 329

    A.6.1 A Matrix Processor . . . . . 329

    A.6.2 A Graphical Curve Processor . . . . . 332

Problems . . . . . 337

**Bibliography** **339**

**Index of MATLAB Functions** **347**

**Index** **350**