Advanced Control Engineering

Roland S. Burns

Professor of Control Engineering
Department of Mechanical and Marine Engineering
University of Plymouth, UK

BUTTERWORTH HEINEMANN

OXFORD AUCKLAND BOSTON JOHANNESBURG MELBOURNE NEW DELHI

Dipindai dengan CamScanner

Contents

Preface and acknowledgements xii

1 INTRODUCTION TO CONTROL ENGINEERING **1**
1.1 Historical review 1
1.2 Control system fundamentals 3
1.2.1 Concept of a system 3
1.2.2 Open-loop systems 5
1.2.3 Closed-loop systems 5
1.3 Examples of control systems 6
1.3.1 Room temperature control system 6
1.3.2 Aircraft elevator control 7
1.3.3 Computer Numerically Controlled (CNC) machine tool 8
1.3.4 Ship autopilot control system 9
1.4 Summary 10
1.4.1 Control system design 10

2 SYSTEM MODELLING **13**
2.1 Mathematical models 13
2.2 Simple mathematical model of a motor vehicle 13
2.3 More complex mathematical models 14
2.3.1 Differential equations with constant coefficients 15
2.4 Mathematical models of mechanical systems 15
2.4.1 Stiffness in mechanical systems 15
2.4.2 Damping in mechanical systems 16
2.4.3 Mass in mechanical systems 17
2.5 Mathematical models of electrical systems 21
2.6 Mathematical models of thermal systems 25
2.6.1 Thermal resistance R_T 25
2.6.2 Thermal capacitance C_T 26
2.7 Mathematical models of fluid systems 27
2.7.1 Linearization of nonlinear functions for small perturbations 27
2.8 Further problems 31

Dipindai dengan CamScanner

Contents

3 TIME DOMAIN ANALYSIS 35
3.1 Introduction 35
3.2 Laplace transforms 36
3.2.1 Laplace transforms of common functions 37
3.2.2 Properties of the Laplace transform 37
3.2.3 Inverse transformation 38
3.2.4 Common partial fraction expansions 39
3.3 Transfer functions 39
3.4 Common time domain input functions 41
3.4.1 The impulse function 41
3.4.2 The step function 41
3.4.3 The ramp function 42
3.4.4 The parabolic function 42
3.5 Time domain response of first-order systems 43
3.5.1 Standard form 43
3.5.2 Impulse response of first-order systems 44
3.5.3 Step response of first-order systems 45
3.5.4 Experimental determination of system time constant using step response 46
3.5.5 Ramp response of first-order systems 47
3.6 Time domain response of second-order systems 49
3.6.1 Standard form 49
3.6.2 Roots of the characteristic equation and their relationship to damping in second-order systems 49
3.6.3 Critical damping and damping ratio 51
3.6.4 Generalized second-order system response to a unit step input 52
3.7 Step response analysis and performance specification 55
3.7.1 Step response analysis 55
3.7.2 Step response performance specification 57
3.8 Response of higher-order systems 58
3.9 Further problems 60

4 CLOSED-LOOP CONTROL SYSTEMS 63
4.1 Closed-loop transfer function 63
4.2 Block diagram reduction 64
4.2.1 Control systems with multiple loops 64
4.2.2 Block diagram manipulation 67
4.3 Systems with multiple inputs 69
4.3.1 Principle of superposition 69
4.4 Transfer functions for system elements 71
4.4.1 DC servo-motors 71
4.4.2 Linear hydraulic actuators 75
4.5 Controllers for closed-loop systems 81
4.5.1 The generalized control problem 81
4.5.2 Proportional control 82
4.5.3 Proportional plus Integral (PI) control 84

Dipindai dengan CamScanner

4.5.4 Proportional plus Integral plus Derivative (PID) control 89
4.5.5 The Ziegler–Nichols methods for tuning PID controllers 90
4.5.6 Proportional plus Derivative (PD) control 92
4.6 Case study examples 92
4.7 Further problems 104

5 CLASSICAL DESIGN IN THE *s*-PLANE 110
5.1 Stability of dynamic systems 110
5.1.1 Stability and roots of the characteristic equation 112
5.2 The Routh–Hurwitz stability criterion 112
5.2.1 Maximum value of the open-loop gain constant for the stability of a closed-loop system 114
5.2.2 Special cases of the Routh array 117
5.3 Root-locus analysis 118
5.3.1 System poles and zeros 118
5.3.2 The root locus method 119
5.3.3 General case for an underdamped second-order system 122
5.3.4 Rules for root locus construction 123
5.3.5 Root locus construction rules 125
5.4 Design in the *s*-plane 132
5.4.1 Compensator design 133
5.5 Further problems 141

6 CLASSICAL DESIGN IN THE FREQUENCY DOMAIN 145
6.1 Frequency domain analysis 145
6.2 The complex frequency approach 147
6.2.1 Frequency response characteristics of first-order systems 147
6.2.2 Frequency response characteristics of second-order systems 150
6.3 The Bode diagram 151
6.3.1 Summation of system elements on a Bode diagram 152
6.3.2 Asymptotic approximation on Bode diagrams 153
6.4 Stability in the frequency domain 161
6.4.1 Conformal mapping and Cauchy's theorem 161
6.4.2 The Nyquist stability criterion 162
6.5 Relationship between open-loop and closed-loop frequency response 172
6.5.1 Closed-loop frequency response 172
6.6 Compensator design in the frequency domain 178
6.6.1 Phase lead compensation 179
6.6.2 Phase lag compensation 189
6.7 Relationship between frequency response and time response for closed-loop systems 191
6.8 Further problems 193

7 DIGITAL CONTROL SYSTEM DESIGN 198
7.1 Microprocessor control 198
7.2 Shannon's sampling theorem 200

Dipindai dengan CamScanner

7.3 Ideal sampling 201
7.4 The z-transform 202
7.4.1 Inverse transformation 204
7.4.2 The pulse transfer function 206
7.4.3 The closed-loop pulse transfer function 209
7.5 Digital control systems 210
7.6 Stability in the z-plane 213
7.6.1 Mapping from the s-plane into the z-plane 213
7.6.2 The Jury stability test 215
7.6.3 Root locus analysis in the z-plane 218
7.6.4 Root locus construction rules 218
7.7 Digital compensator design 220
7.7.1 Digital compensator types 221
7.7.2 Digital compensator design using pole placement 224
7.8 Further problems 229

8 STATE-SPACE METHODS FOR CONTROL SYSTEM DESIGN 232
8.1 The state-space-approach 232
8.1.1 The concept of state 232
8.1.2 The state vector differential equation 233
8.1.3 State equations from transfer functions 238
8.2 Solution of the state vector differential equation 239
8.2.1 Transient solution from a set of initial conditions 241
8.3 Discrete-time solution of the state vector differential equation 244
8.4 Control of multivariable systems 248
8.4.1 Controllability and observability 248
8.4.2 State variable feedback design 249
8.4.3 State observers 254
8.4.4 Effect of a full-order state observer on a closed-loop system 260
8.4.5 Reduced-order state observers 262
8.5 Further problems 266

9 OPTIMAL AND ROBUST CONTROL SYSTEM DESIGN 272
9.1 Review of optimal control 272
9.1.1 Types of optimal control problems 272
9.1.2 Selection of performance index 273
9.2 The Linear Quadratic Regulator 274
9.2.1 Continuous form 274
9.2.2 Discrete form 276
9.3 The linear quadratic tracking problem 280
9.3.1 Continuous form 280
9.3.2 Discrete form 281
9.4 The Kalman filter 284
9.4.1 The state estimation process 284
9.4.2 The Kalman filter single variable estimation problem 285
9.4.3 The Kalman filter multivariable state estimation problem 286

Dipindai dengan CamScanner

9.5	Linear Quadratic Gaussian control system design		288
9.6	Robust control		299
	9.6.1	Introduction	299
	9.6.2	Classical feedback control	300
	9.6.3	Internal Model Control (IMC)	301
	9.6.4	IMC performance	302
	9.6.5	Structured and unstructured model uncertainty	303
	9.6.6	Normalized system inputs	304
9.7	H_2- and H_∞-optimal control		305
	9.7.1	Linear quadratic H_2-optimal control	305
	9.7.2	H_∞-optimal control	306
9.8	Robust stability and robust performance		306
	9.8.1	Robust stability	306
	9.8.2	Robust performance	308
9.9	Multivariable robust control		314
	9.9.1	Plant equations	314
	9.9.2	Singular value loop shaping	315
	9.9.3	Multivariable H_2 and H_∞ robust control	316
	9.9.4	The weighted mixed-sensitivity approach	317
9.10	Further problems		321
10	**INTELLIGENT CONTROL SYSTEM DESIGN**		**325**
10.1	Intelligent control systems		325
	10.1.1	Intelligence in machines	325
	10.1.2	Control system structure	325
10.2	Fuzzy logic control systems		326
	10.2.1	Fuzzy set theory	326
	10.2.2	Basic fuzzy set operations	328
	10.2.3	Fuzzy relations	330
	10.2.4	Fuzzy logic control	331
	10.2.5	Self-organizing fuzzy logic control	344
10.3	Neural network control systems		347
	10.3.1	Artificial neural networks	347
	10.3.2	Operation of a single artificial neuron	348
	10.3.3	Network architecture	349
	10.3.4	Learning in neural networks	350
	10.3.5	Back-Propagation	351
	10.3.6	Application of neural networks to modelling, estimation and control	358
	10.3.7	Neurofuzzy control	361
10.4	Genetic algorithms and their application to control system design		365
	10.4.1	Evolutionary design techniques	365
	10.4.2	The genetic algorithm	365
	10.4.3.	Alternative search strategies	372
10.5	Further problems		373

Dipindai dengan CamScanner

APPENDIX 1 CONTROL SYSTEM DESIGN USING MATLAB 380

APPENDIX 2 MATRIX ALGEBRA 424

References and further reading 428
Index 433

Dipindai dengan CamScanner