

Contents

I	Continuous Time Control	xvii
1	Dynamic Modeling of Chemical Processes	1
1.1	References	1
1.2	Applications of Process Control	1
1.3	Description of a Process from the Control Engineer's Point of View	2
1.4	Model Classification	5
1.5	State Space Models	6
1.6	Examples of Models in Chemical Engineering	7
1.6.1	Lumped Parameter Systems	7
1.6.2	Distributed Parameter Systems	16
1.6.3	Degrees of Freedom	17
1.7	Process Stability	18
1.8	Order of a System	18
1.9	Laplace Transform	19
1.9.1	Linearization and Deviation Variables	20
1.9.2	Some Important Properties of Laplace Transformation	22
1.9.3	Transfer Function	25
1.9.4	Poles and Zeros of a Transfer Function	33
1.9.5	Qualitative Analysis of a System Response	33
1.10	Linear Systems in State Space	37
1.10.1	General Case	37
1.10.2	Analog Representation	38
1.11	Dynamic Behavior of Simple Processes	40
1.11.1	First-Order Systems	41
1.11.2	Integrating Systems	43
1.11.3	Second-Order Systems	44
1.11.4	Higher-Order Systems	48
1.11.5	Process Identification in the Continuous Domain	55
2	Linear Feedback Control	63
2.1	Design of a Feedback Loop	63
2.1.1	Block Diagram of the Feedback Loop	63
2.1.2	General Types of Controllers	65

2.1.3	Sensors	67
2.1.4	Transmission Lines	69
2.1.5	Actuators	69
2.2	Block Diagrams, Signal-flow Graphs, Calculation Rules	71
2.3	Dynamics of Feedback Controlled Processes	80
2.3.1	Study of Different Actions	83
2.3.2	Influence of Proportional Action	84
2.3.3	Influence of Integral Action	88
2.3.4	Influence of Derivative Action	91
2.3.5	Summary of Controllers Characteristics	95
3	Stability Analysis	101
3.1	Case of a System Defined by its Transfer Function	101
3.2	State Space Analysis	102
3.2.1	General Analysis for a Continuous Nonlinear System	102
3.2.2	Case of a Linear Continuous System	107
3.2.3	Case of a Nonlinear Continuous System: the Polymerization Reactor	109
3.2.4	State Space analysis of a Linear System	115
3.3	Stability Analysis of Feedback Systems	116
3.3.1	Routh-Hurwitz Criterion	117
3.3.2	Root locus Analysis	119
3.3.3	Frequency Method	123
4	Design of Feedback Controllers	127
4.1	Performance Criteria	127
4.2	Transient Response Characteristics	129
4.3	Performance Criteria for Design	129
4.4	Choice of PID Controller	132
4.4.1	General Remarks	132
4.4.2	Recommendations	133
4.5	PID Controller Tuning	134
4.5.1	Tuning by Trial and Error	134
4.5.2	Sustained Oscillation Method	135
4.5.3	Relay Oscillation Method	136
4.5.4	Process Reaction Curve Method	141
4.6	PID Improvement	144
4.6.1	PID Controller with Derivative Action on the Measured Output	144
4.6.2	Use of a Reference Trajectory	144
4.6.3	Discretized PID Controller	145
4.6.4	Anti-Windup Controller	147
4.6.5	PID Control by On-Off Action	149
4.6.6	pH Control	150
4.7	Direct Synthesis Method	155
4.8	Internal Model Control	157

4.9	Pole Placement	163
4.9.1	Robustness of Pole Placement Control	169
4.9.2	Unitary Feedback Controller	171
4.10	Linear Quadratic Control	171
4.10.1	Regulation Behavior	172
4.10.2	Tracking Behavior	173
5	Frequency Analysis	181
5.1	Response of a Linear System to a Sinusoidal Input	181
5.1.1	Case of a First Order Process	181
5.1.2	Note on Complex Numbers	183
5.1.3	Case of any Linear Process	184
5.1.4	Case of Linear Systems in Series	185
5.2	Graphical Representation	186
5.2.1	Bode Plot	186
5.2.2	n^{th} Order System	188
5.2.3	Nyquist Plot	189
5.2.4	n^{th} Order System	191
5.2.5	Black Plot	192
5.3	Characterization of a System by Frequency Analysis	193
5.4	Frequency Response of Feedback Controllers	194
5.4.1	Proportional Controller	194
5.4.2	Proportional-Integral Controller	194
5.4.3	Ideal Proportional-Derivative Controller	195
5.4.4	Proportional-Integral-Derivative Controller	196
5.5	Bode Stability Criterion	199
5.6	Gain and Phase Margins	204
5.6.1	Gain Margin	205
5.6.2	Phase Margin	205
5.7	Nyquist Stability Criterion	209
5.8	Closed Loop Frequency Response	213
5.9	Internal Model Principle	218
5.10	Robustness	219
5.11	Summary for Controller Design	235
6	Improvement of Control Systems	237
6.1	Compensation of Time Delay	237
6.2	Inverse Response Compensation	239
6.3	Cascade Control	242
6.4	Selective Control	247
6.5	Split-Range Control	248
6.6	Feedforward Control	249
6.6.1	Generalities	249
6.6.2	Application in Distillation	250
6.6.3	Synthesis of a Feedforward Controller	251
6.6.4	Realization of a Feedforward Controller	253

6.6.5	Feedforward and Feedback Control	255
6.7	Ratio Control	256
7	State Representation, Controllability, Observability	259
7.1	State Representation	259
7.1.1	Monovariable System	259
7.1.2	Multivariable System	261
7.2	Controllability	262
7.3	Observability	266
7.4	Realizations	269
7.5	Remark on Controllability and Observability in Discrete Time .	274
II	Multivariable Control	275
8	Multivariable Control by Transfer Function Matrix	277
8.1	Introduction	277
8.2	Representation of a Multivariable Process by Transfer Function Matrix	277
8.3	Stability Study	280
8.3.1	Smith-McMillan Form	280
8.3.2	Poles and Zeros of a Transfer Function Matrix	280
8.3.3	Generalized Nyquist Criterion	280
8.3.4	Characteristic Loci	281
8.3.5	Gershgorin Circles	282
8.3.6	Niederlinski Index	284
8.4	Interaction and Decoupling	284
8.4.1	Decoupling for a 2×2 System	284
8.4.2	Disturbance Rejection	289
8.4.3	Singular Value Decomposition	289
8.4.4	Relative Gain Array	290
8.4.5	Gershgorin Circles and Interaction	296
8.5	Multivariable Robustness	296
8.6	Robustness Study of a 2×2 Distillation Column	301
8.6.1	Simplified Decoupling Analysis	302
8.6.2	Ideal Decoupling Analysis	302
8.6.3	One-way Decoupling Analysis	303
8.6.4	Comparison of the Three Previous Decouplings	303
8.7	Synthesis of a Multivariable Controller	303
8.7.1	Controllers Tuning	304
8.8	Discrete Multivariable Internal Model Control	305
III	Discrete Time Identification	311
9	Discrete-Time Generalities and Basic Signal Processing	313
9.1	Fourier Transformation and Signal Processing	314

9.1.1	Continuous Fourier Transform	314
9.1.2	Discrete Fourier Transform	320
9.1.3	Stochastic Signals	323
9.1.4	Stochastic Stationary Signals	324
9.1.5	Summary	325
9.2	Sampling	329
9.2.1	DA and AD Conversions	329
9.2.2	Choice of the Sampling Period	330
9.3	Filtering	336
9.3.1	First Order Filter	337
9.3.2	Second Order Filter	338
9.3.3	Moving Average Filter	339
9.3.4	Fast Transient Filter	339
9.4	Discrete Time and Finite Differences Models	340
9.5	Different Discrete Representations of a System	342
9.5.1	Discrete Representation: z Transform	342
9.5.2	Conversion of a Continuous Description in Discrete Time	361
9.5.3	Operators	364
10	Identification Principles	371
10.1	System Description	371
10.1.1	System without Disturbance	371
10.1.2	Disturbance Representation	372
10.2	Non Parametric Identification	373
10.2.1	Frequency Identification	373
10.2.2	Identification by Correlation Analysis	374
10.2.3	Spectral Identification	376
10.3	Parametric Identification	379
10.3.1	Prediction Principles	379
10.3.2	One-step Prediction	380
10.3.3	p -step Predictions	385
11	Models and Methods for Parametric Identification	387
11.1	Model Structure for Parametric Identification	387
11.1.1	Linear Models of Transfer Functions	387
11.1.2	Models for Estimation in State Space	398
11.2	Models of Time-Varying Linear Systems	406
11.3	Linearization of Nonlinear Time-Varying Models	407
11.4	Principles of Parametric Estimation	407
11.4.1	Minimization of Prediction Errors	407
11.4.2	Linear Regressions and Least Squares	409
11.4.3	Maximum Likelihood Method	412
11.4.4	Correlation of Prediction Errors with Past Data	415
11.4.5	Instrumental Variable Method	416

12 Parametric Estimation Algorithms	421
12.1 Linear Regression and Least Squares	421
12.2 Gradient Methods	423
12.2.1 Gradient Method Based on a Priori Error	424
12.2.2 Gradient Method Based on a Posteriori Error	427
12.3 Recursive Algorithms	429
12.3.1 Simple Recursive Least Squares	429
12.3.2 Recursive Extended Least Squares	438
12.3.3 Recursive Generalized Least Squares	438
12.3.4 Recursive Maximum Likelihood	439
12.3.5 Recursive Prediction Error Method	440
12.3.6 Instrumental Variable Method	443
12.3.7 Output Error Method	444
12.4 Algorithm Robustification	444
12.5 Validation	447
12.6 Input Sequences for Identification	447
12.7 Identification Examples	450
12.7.1 Academic Example of a Second Order System	450
12.7.2 Identification of a Simulated Chemical Reactor	455
IV Discrete Time Control	459
13 Digital Control	461
13.1 Pole Placement Control	461
13.1.1 Influence of Pole Position	461
13.1.2 Control Synthesis by Pole Placement	461
13.1.3 Relation between Pole Placement and State Feedback	468
13.1.4 General Pole Placement Design	472
13.1.5 Digital PID Controller	479
13.2 Discrete Internal Model Control	481
13.3 Generalities on Adaptive Control	487
14 Optimal Control	491
14.1 Introduction	491
14.2 Problem Statement	492
14.3 Variational Method in the Mathematical Framework	494
14.3.1 Variation of the Criterion	495
14.3.2 Variational Problem without Constraints, Fixed Bound- aries	497
14.3.3 Variational Problem with Constraints, General Case	497
14.3.4 Hamilton-Jacobi Equation	500
14.4 Optimal Control	502
14.4.1 Variational Methods	502
14.4.2 Variation of the criterion	503

14.4.3	Euler Conditions	504
14.4.4	Weierstrass Condition and Hamiltonian Maximization .	506
14.4.5	Hamilton-Jacobi Conditions and Equation	507
14.4.6	Maximum Principle	509
14.4.7	Singular arcs	511
14.4.8	Numerical issues	518
14.5	Dynamic Programming	523
14.5.1	Classical Dynamic Programming	523
14.5.2	Hamilton-Jacobi-Bellman equation	527
14.6	Linear Quadratic Control	528
14.6.1	Continuous Time Linear Quadratic Control	528
14.6.2	Linear Quadratic Gaussian Control	537
14.6.3	Discrete Time Linear Quadratic Control	542
15	Generalized Predictive Control	553
15.1	Interest of Generalized Predictive Control	553
15.2	Brief Overview of Predictive Control Evolution	554
15.3	Simple Generalized Predictive Control	555
15.3.1	Theoretical Presentation	555
15.3.2	<i>Numerical Example</i> : Generalized Predictive Control of a Chemical Reactor	559
15.3.3	GPC seen as a Pole Placement	560
15.4	Generalized Predictive Control with Multiple Reference Model	562
15.4.1	Theoretical Presentation	562
15.4.2	<i>Numerical Example</i> : Generalized Predictive Control with Performance Model of a Chemical Reactor	565
15.5	Partial State Reference Model Control	566
15.6	Generalized Predictive Control of a Chemical Reactor	566
16	Model Predictive Control	573
16.1	A General View of Model Predictive Control	573
16.2	Linear Model Predictive Control	579
16.2.1	In Absence of Constraints	579
16.2.2	In Presence of Constraints	579
16.2.3	Short Description of IDCOM	579
16.2.4	Dynamic Matrix Control (DMC)	580
16.2.5	Quadratic Dynamic Matrix Control (QDMC)	587
16.2.6	State-Space Formulation of Dynamic Matrix Control . .	588
16.2.7	State-Space Linear Model Predictive Control as OB MPC	589
16.2.8	State-Space Linear Model Predictive Control as General Optimization	592
16.3	Nonlinear Model Predictive Control	594
16.3.1	Nonlinear Quadratic Dynamic Matrix Control (NLQDMC)	594
16.3.2	Other Approaches of Nonlinear Model Predictive Control	595
16.4	Model Predictive Control of a FCC	598

16.4.1 FCC Modeling	598
-------------------------------	-----

V Nonlinear Control 615

17 Nonlinear Geometric Control 617

17.1 Some Linear Notions Useful in Nonlinear	618
17.1.1 Influence of a Coordinate Change in Linear	618
17.1.2 Relative Degree	619
17.1.3 Normal Form and Relative Degree	620
17.1.4 Zero Dynamics	622
17.1.5 Static State Feedback	623
17.1.6 Pole Placement by Static State Feedback	623
17.1.7 Input-Output Pole Placement	625
17.2 Monovariabale Nonlinear Control	625
17.2.1 Some Notions of Differential Geometry	625
17.2.2 Relative Degree of a Monovariabale Nonlinear System . .	627
17.2.3 Frobenius Theorem	628
17.2.4 Coordinates Change	630
17.2.5 Normal Form	631
17.2.6 Controllability and Observability	632
17.2.7 Principle of Feedback Linearization	633
17.2.8 Exact Input-State Linearization for a System of Relative Degree Equal to n	633
17.2.9 Input-Output Linearization of a System with Relative Degree r Lower or Equal to n	636
17.2.10 Zero Dynamics	637
17.2.11 Asymptotic Stability	639
17.2.12 Tracking of a Reference Trajectory	641
17.2.13 Decoupling with Respect to a Disturbance	642
17.2.14 Case of Nonminimum Phase Systems	644
17.2.15 Globally Linearizing Control	644
17.3 Multivariable Nonlinear Control	645
17.3.1 Relative Degree	645
17.3.2 Coordinate Change	646
17.3.3 Normal Form	647
17.3.4 Zero Dynamics	648
17.3.5 Exact Linearization by State Feedback and Diffeomorphism	648
17.3.6 Nonlinear Control Perfectly Decoupled by Static State Feedback	649
17.3.7 Obtaining a Relative Degree by Dynamic Extension . .	650
17.3.8 Nonlinear Adaptive Control	651
17.4 Applications of Nonlinear Geometric Control	652

18 State Observers	655
18.1 Introduction	655
18.1.1 Indirect Sensors	656
18.1.2 Observer Principle	656
18.2 Parameter Estimation	657
18.3 Statistical Estimation	657
18.3.1 About the Data	658
18.3.2 Principal Component Analysis	658
18.3.3 Partial Least Squares	660
18.4 Observers	662
18.4.1 Luenberger Observer	662
18.4.2 Linear Kalman Filter	662
18.4.3 Extended Kalman Filter (EKF) under Continuous-Discrete Form	662
18.4.4 Globally Linearizing Observer	664
18.4.5 High Gain Observer	666
18.5 Conclusion	667
VI Applications to Processes	671
19 Nonlinear Control of Reactors with State Estimation	673
19.1 Introduction	673
19.2 Chemical Reactor	673
19.2.1 Model of the Chemical Reactor	674
19.2.2 Control Problem Setting	675
19.2.3 Control Law	676
19.2.4 State Estimation	679
19.2.5 Simulation Results	680
19.3 Biological Reactor	684
19.3.1 Introduction	684
19.3.2 Dynamic Model of the Biological Reactor	685
19.3.3 Synthesis of the Nonlinear Control Law	687
19.3.4 Simulation Conditions	689
19.3.5 Simulation Results	691
19.3.6 Conclusion	691
20 Distillation Column Control	695
20.1 Generalities on Distillation Columns Behavior	695
20.2 Dynamic Model of the Distillation Column	698
20.3 Generalities on Distillation Column Control	702
20.4 Different Types of Distillation Column Control	703
20.4.1 Single-Input Single-Output Control	703
20.4.2 Dual Decoupling Control	704
20.4.3 The Column as a 5×5 System	706
20.4.4 Linear Digital Control	708

20.4.5	Model Predictive Control	710
20.4.6	Bilinear Models	711
20.4.7	Nonlinear Control	713
20.5	Conclusion	717
21	Examples and Benchmarks of Typical Processes	723
21.1	Single Input-Single Output Processes	723
21.1.1	Description by Transfer Functions	723
21.1.2	Description by a State-Space Knowledge Model	724
21.1.3	Description by a Linear State-Space Model	730
21.2	Multivariable Processes	730
21.2.1	Matrices of Continuous Transfer Functions	730
21.2.2	Description by a Linear State-Space Model	733
21.2.3	Description by a State-Space Knowledge Model	735
21.2.4	Continuous State-Space Models	737