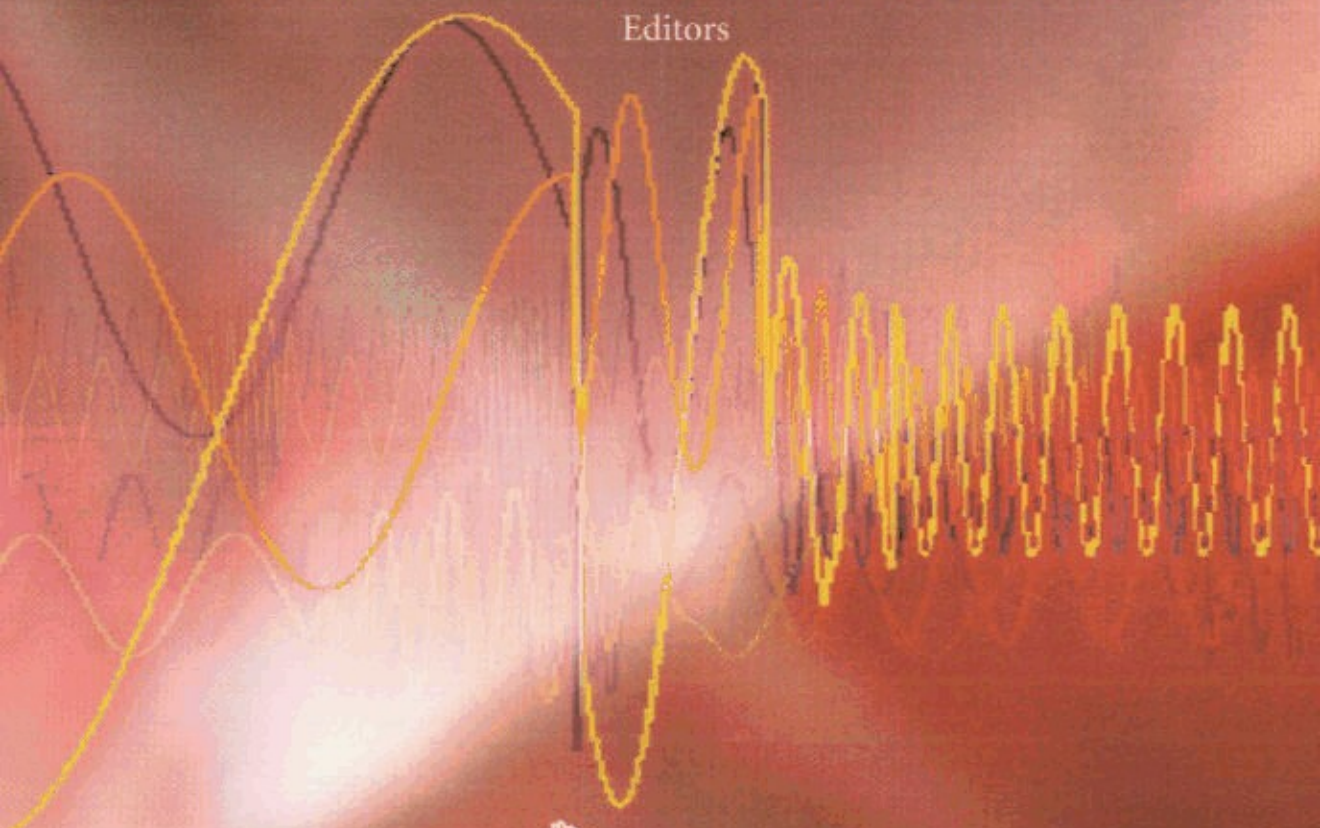
PID Control

New Identification and Design Methods

MICHAEL A. JOHNSON · MOHAMMAD H. MORADI

Editors



Springer

Contents

Editorial Responsibilities xix

Notation xxv

1 PID Control Technology 1
Learning Objectives 1
1.1 Basic Industrial Control 2
1.1.1 Process Loop Issues – a Summary Checklist 6
1.2 Three-Term Control 7
1.2.1 Parallel PID Controllers 9
1.2.2 Conversion to Time constant PID Forms 10
1.2.3 Series PID Controllers 12
1.2.4 Simple PID Tuning 14
1.3 PID Controller Implementation Issues 17
1.3.1 Bandwidth-Limited Derivative Control 18
1.3.2 Proportional Kick 22
1.3.3 Derivative Kick 24
1.3.4 Integral Anti-Windup Circuits 26
1.3.5 Reverse-Acting Controllers 29
1.4 Industrial PID Control 29
1.4.1 Traditional Industrial PID Terms 30
1.4.2 Industrial PID Structures and Nomenclature 32
1.4.3 The Process Controller Unit 33
1.4.4 Supervisory Control and the SCADA PID Controller 35
Acknowledgements 46
References 46

2 Some PID Control Fundamentals 47
Learning Objectives 47
2.1 Process System Models 48
2.1.1 State Space Models 49
2.1.2 Convolution Integral Process Models 52
2.1.3 Laplace Transfer Function Models 53

2.1.4 Common Laplace Transform Process Models . . . 55
2.2 Controller Degrees of Freedom Structure . . . 57
2.2.1 One Degree of Freedom Control . . . 57
2.2.2 Two Degree of Freedom Control . . . 57
2.2.3 Three Degree of Freedom Structures . . . 59
2.3 PID Control Performance . . . 60
2.3.1 Controller Performance Assessment – General Considerations . . . 60
2.3.2 Controller Assessment – the Effectiveness of PID Control . . . 66
2.3.3 Classical Stability Robustness Measures . . . 73
2.3.4 Parametric Stability Margins for Simple Processes . . . 79
2.4 State Space Systems and PID Control . . . 88
2.4.1 Linear Reference Error Feedback Control . . . 88
2.4.2 Two Degree of Freedom Feedback Control System . . . 90
2.4.3 State Feedback With Integral Error Feedback Action . . . 91
2.4.4 State Space Analysis for Classical PI Control Structure . . . 95
2.5 Multivariable PID Control Systems . . . 99
2.5.1 Multivariable Control . . . 100
2.5.2 Cascade Control Systems . . . 103
Acknowledgements . . . 106
References . . . 106

3 On-line Model-Free Methods . . . 109
Learning Objectives . . . 109
3.1 Introduction . . . 110
3.1.1 A Model-Free Control Design Paradigm . . . 110
3.2 Iterative Feedback Tuning . . . 114
3.2.1 Generating the Cost Function Gradient . . . 114
3.2.2 Case Study – a Wastewater Process Example . . . 117
3.2.3 Some Remarks on Iterative Feedback Tuning . . . 122
3.3 The Controller Parameter Cycling Tuning Method . . . 124
3.3.1 Generating the Gradient and Hessian – Some Theory . . . 125
3.3.2 Issues for a Controller Parameter Cycling Algorithm . . . 131
3.3.3 The Controller Parameter Cycling Algorithm . . . 135
3.3.4 Case Study – Multivariable Decentralised Control . . . 136
3.4 Summary and Future Directions . . . 143
Acknowledgements . . . 144
Appendix 3.A . . . 144
References . . . 145

4 Automatic PID Controller Tuning – the Nonparametric Approach . . . 147
Learning Objectives . . . 147
4.1 Introduction . . . 148
4.2 Overview of Nonparametric Identification Methods . . . 149
4.2.1 Transient Response Methods . . . 149
4.2.2 Relay Feedback Methods . . . 150
4.2.3 Fourier Methods . . . 150
4.2.4 Phase-Locked Loop Methods . . . 151

4.3 Frequency Response Identification with Relay Feedback . . . 152
4.3.1 Basic Idea . . . 153
4.3.2 Improved Estimation Accuracy . . . 155
4.3.3 Estimation of a General Point . . . 161
4.3.4 Estimation of Multiple Points . . . 164
4.3.5 On-line relay tuning . . . 164
4.4 Sensitivity Assessment Using Relay Feedback . . . 166
4.4.1 Control Robustness . . . 166
4.4.2 Maximum Sensitivity . . . 167
4.4.3 Construction of the $\lambda - \phi$ Chart . . . 168
4.4.4 Stability Margins Assessment . . . 170
4.5 Conversion to Parametric Models . . . 171
4.5.1 Single and Multiple Lag Processes . . . 172
4.5.2 Second-Order Modelling . . . 174
4.6 Case Studies . . . 174
Case Study 4.1: Improved Estimation Accuracy for the Relay Experiment . . . 176
Case Study 4.2: Estimation of a General Point . . . 177
Case Study 4.3: Estimation of Multiple Points . . . 177
Case Study 4.4: On-line Relay Tuning . . . 179
Case Study 4.5: Sensitivity Assessment . . . 179
References . . . 180

5 Relay Experiments for Multivariable Systems . . . 183
Learning Objectives . . . 183
5.1 Introduction . . . 184
5.2 Critical Points of a System . . . 185
5.2.1 Critical Points for Two-Input, Two-Output Systems . . . 185
5.2.2 Critical Points for MIMO Systems . . . 186
5.3 Decentralised Relay Experiments for Multivariable Systems . . . 187
5.3.1 Finding System Gains at Particular Frequencies . . . 188
5.3.2 Decentralised Relay Control Systems – Some Theory . . . 190
5.3.3 A Decentralised Two-Input, Two-Output PID Control System Relay-Based Procedure . 191
5.4 A Decentralised Multi-Input, Multi-Output PID Control System Relay-Based Procedure . . . 197
5.5 PID Control Design at Bandwidth Frequency . . . 202
5.6 Case Studies . . . 207
5.6.1 Case Study 1: The Wood and Berry Process System Model . . . 207
5.6.2 Case Study 2: A Three-Input, Three-Output Process System . . . 210
5.7 Summary . . . 210
References . . . 211

6 Phase-Locked Loop Methods . . . 213
Learning Objectives . . . 213
6.1 Introduction . . . 214
6.1.1 The Relay Experiment . . . 215
6.1.2 Implementation Issues for the Relay Experiment . . . 216
6.1.3 Summary Conclusions on the Relay Experiment . . . 220
6.2 Some Constructive Numerical Solution Methods . . . 221

6.2.1 Bisection Method . . . 222
6.2.2 *Prediction Method* . . . 224
6.2.3 Bisection and Prediction Method – a Comparison and Assessment . . . 227
6.3 Phase-Locked Loop Identifier Module – Basic Theory . . . 229
6.3.1 The Digital Identifier Structure . . . 230
6.3.2 Noise Management Techniques . . . 242
6.3.3 Disturbance Management Techniques . . . 248
6.4 Summary and Discussion . . . 255
References . . . 256

7 Phase-Locked Loop Methods and PID Control . . . 259
Learning Objectives . . . 259
7.1 Introduction – Flexibility and Applications . . . 260
7.2 Estimation of the Phase Margin . . . 260
7.3 Estimation of the Parameters of a Second-Order Underdamped System . . . 261
7.4 Identification of Systems in Closed Loop . . . 265
7.4.1 Identification of an Unknown System in Closed Loop with an Unknown Controller . . . 265
7.4.2 Identification of an Unknown System in Closed Loop with a Known Controller . . . 268
7.5 Automated *PI* Control Design . . . 270
7.5.1 Identification Aspects for Automated PID Control Design . . . 271
7.5.2 PI Control with Automated Gain and Phase Margin Design . . . 275
7.5.3 PI Control with Automated Maximum Sensitivity and Phase Margin Design . . . 286
7.6 Conclusions . . . 294
References . . . 295

8 Process Reaction Curve and Relay Methods Identification and PID Tuning . . . 297
Learning Objectives . . . 297
8.1 Introduction . . . 298
8.2 Developing Simple Models from the Process Reaction Curve . . . 302
8.2.1 Identification Algorithm for Oscillatory Step Responses . . . 303
8.2.2 Identification Algorithm for Non-Oscillatory Responses Without Overshoot . . . 305
8.3 Developing Simple Models from a Relay Feedback Experiment . . . 310
8.3.1 On-line Identification of FOPDT Models . . . 312
8.3.2 On-line Identification of SOPDT Models . . . 314
8.3.3 Examples for the On-line Relay Feedback Procedure . . . 315
8.3.4 Off-line Identification . . . 317
8.4 An Inverse Process Model-Based Design Procedure for PID Control . . . 320
8.4.1 Inverse Process Model-Based Controller Principles . . . 320
8.4.2 PI/PID Controller Synthesis . . . 323
8.4.3 Autotuning of PID Controllers . . . 325
8.5 Assessment of PI/PID Control Performance . . . 329
8.5.1 Achievable Minimal IAE Cost and Rise Time . . . 329
8.5.2 Assessment of PI/PID Controllers . . . 332
References . . . 336

9 Fuzzy Logic and Genetic Algorithm Methods in PID Tuning . . . 339
Learning Objectives . . . 339

9.1 Introduction . . . 340
9.2 Fuzzy PID Controller Design . . . 340
9.2.1 Fuzzy PI Controller Design . . . 342
9.2.2 Fuzzy D Controller Design . . . 343
9.2.3 Fuzzy PID Controller Design . . . 344
9.2.4 Fuzzification . . . 345
9.2.5 Fuzzy Control Rules . . . 346
9.2.6 Defuzzification . . . 346
9.2.7 A Control Example . . . 349
9.3 Multi-Objective Optimised Genetic Algorithm Fuzzy PID Control . . . 350
9.3.1 Genetic Algorithm Methods Explained . . . 351
9.3.2 Case study A: Multi-Objective Genetic Algorithm Fuzzy PID Control of a Nonlinear Plant . . . 353
9.3.3 Case study B: Control of Solar Plant . . . 354
9.4 Applications of Fuzzy PID Controllers to Robotics . . . 355
9.5 Conclusions and Discussion . . . 357
Acknowledgments . . . 358
References . . . 358

10 Tuning PID Controllers Using Subspace Identification Methods . . . 361
Learning Objectives . . . 361
10.1 Introduction . . . 362
10.2 A Subspace Identification Framework for Process Models . . . 363
10.2.1 The Subspace Identification Framework . . . 363
10.2.2 Incremental Subspace Representations . . . 366
10.3 Restricted Structure Single-Input, Single-Output Controllers . . . 368
10.3.1 Controller Parameterisation . . . 369
10.3.2 Controller Structure and Computations . . . 370
10.4 Restricted-Structure Multivariable Controller Characterisation . . . 371
10.4.1 Controller Parameterisation . . . 371
10.4.2 Multivariable Controller Structure . . . 372
10.5 Restricted-Structure Controller Parameter Computation . . . 372
10.5.1 Cost Index . . . 373
10.5.2 Formulation as a Least-Squares Problem . . . 373
10.5.3 Computing the Closed-Loop System Condition . . . 374
10.5.4 Closed-Loop Stability Conditions . . . 375
10.5.5 The Controller Tuning Algorithm . . . 375
10.6 Simulation Case Studies . . . 376
10.6.1 Activated Sludge Wastewater Treatment Plant Layout . . . 377
10.6.2 Case study 1: Single-Input, Single-Output Control Structure . . . 378
10.6.3 Case Study 2: Control of Two Reactors with a Lower Triangular Controller Structure . 379
10.6.4 Case Study 3: Control of Three Reactors with a Diagonal Controller Structure . . . 382
10.6.5 Case Study 4: Control of Three Reactors with a Lower Triangular Controller Structure . . 385
References . . . 387

11 Design of Multi-Loop and Multivariable PID Controllers . . . 389
Learning Objectives . . . 389

11.1 Introduction . . . 390
11.1.1 Multivariable Systems . . . 390
11.1.2 Multivariable Control . . . 391
11.1.3 Scope of the Chapter and Some Preliminary Concepts . . . 392
11.2 Multi-Loop PID Control . . . 394
11.2.1 Biggest Log-Modulus Tuning Method . . . 394
11.2.2 Dominant Pole Placement Tuning Method . . . 395
11.2.3 Examples . . . 404
11.3 Multivariable PID Control . . . 408
11.3.1 Decoupling Control and Design Overview . . . 409
11.3.2 Determination of the Objective Loop Performance . . . 412
11.3.3 Computation of PID Controller . . . 421
11.3.4 Examples . . . 422
11.4 Conclusions . . . 426
References . . . 427

12 Restricted Structure Optimal Control . . . 429
Learning Objectives . . . 429
12.1 Introduction to Optimal LQG Control for Scalar Systems . . . 430
12.1.1 System Description . . . 431
12.1.2 Cost Function and Optimisation Problem . . . 432
12.2 Numerical Algorithms for SISO System Restricted Structure Control . . . 436
12.2.1 Formulating a Restricted Structure Numerical Algorithm . . . 436
12.2.2 Iterative Solution for the SISO Restricted Structure LQG Controller . . . 439
12.2.3 Properties of the Restricted Structure LQG Controller . . . 440
12.3 Design of PID Controllers Using the Restricted Structure Method . . . 441
12.3.1 General Principles for Optimal Restricted Controller Design . . . 442
12.3.2 Example of PID Control Design . . . 443
12.4 Multivariable Optimal LQG Control: An Introduction . . . 444
12.4.1 Multivariable Optimal LQG Control and Cost Function Values . . . 448
12.4.2 Design Procedures for an Optimal LQG Controller . . . 451
12.5 Multivariable Restricted Structure Controller Procedure . . . 453
12.5.1 Analysis for a Multivariable Restricted Structures Algorithm . . . 454
12.5.2 Multivariable Restricted Structure Algorithm and Nested Restricted Structure Controllers . . . 458
12.6 An Application of Multivariable Restricted Structure Assessment – Control of the Hotstrip Finishing Mill Looper System . . . 461
12.6.1 The Hotstrip Finishing Mill Looper System . . . 461
12.6.2 An Optimal Multivariable LQG Controller for the Looper System . . . 463
12.6.3 A Controller Assessment Exercise for the Hotstrip Looper System . . . 465
12.7 Conclusions . . . 470
Acknowledgements . . . 471
References . . . 472

13 Predictive PID Control . . . 473
Learning Objectives . . . 473
13.1 Introduction . . . 474

13.2 Classical Process Control Model Methods . . . 475
13.2.1 Smith Predictor Principle . . . 475
13.2.2 Predictive PI With a Simple Model . . . 477
13.2.3 Method Application and an Example . . . 480
13.3 Simple Process Models and GPC-Based Methods . . . 485
13.3.1 Motivation for the Process Model Restriction . . . 485
13.3.2 Analysis for a GPC PID Controller . . . 486
13.3.3 Predictive PID Control: Delay-Free System $h = 0$ . . . 490
13.3.4 Predictive PID Control: Systems with Delay $h > 0$ . . . 491
13.3.5 Predictive PID Control: An Illustrative Example . . . 493
13.4 Control Signal Matching and GPC Methods . . . 500
13.4.1 Design of SISO Predictive PID Controllers . . . 500
13.4.2 Optimal Values of Predictive PID Controller Gains . . . 503
13.4.3 Design of MIMO Predictive PID controllers . . . 515
Acknowledgements . . . 524
Appendix 13.A . . . 524
13.A.1 Proof of Lemma 13.1 . . . 524
13.A.2 Proof of Theorem 13.1 . . . 526
13.A.3 Proof of Lemma 13.2 . . . 527
References . . . 529

About the Contributors . . . 531

Index . . . 539