Contents

List of Figures xvii

List of Tables xxiii

Symbols and Abbreviations xxv
Abbreviations xxv
Scalar and Vector Signals xxvi
General Symbols xxvi
Operators and Functions xxxi
Criteria xxxiii

Chapter 1. Introduction 1
1.1. An Overview of the Recent History of Process Control in Industry 1
1.2. Where are We Today? 2
1.3. The Contribution of this Book 3
1.4. Synopsis 5

Chapter 2. Preliminary Material 7
2.1. Introduction 7
2.2. General Representation of a Closed-loop System and Closed-loop Stability 8
2.2.1. General Closed-loop Set-up 8
2.2.2. Closed-loop Transfer Functions and Stability 9
2.2.3. Some Useful Algebra for the Manipulation of Transfer Matrices 11

2.3. LFT-based Representation of a Closed-loop System 12
2.4. Coprime Factorisations 14
2.4.1. Coprime Factorisations of Transfer Functions or Matrices 14
2.4.2. The Bezout Identity and Closed-loop Stability 18
2.5. The ν-gap Metric 20
2.5.1. Definition 20
2.5.2. Stabilisation of a Set of Systems by a Given Controller and Comparison with the Directed Gap Metric 22
2.5.3. The ν-gap Metric and Robust Stability 23
2.6. Prediction-error Identification 24
2.6.1. Signals Properties 25
2.6.2. The Identification Method 26
2.6.3. Usual Model Structures 28
2.6.4. Computation of the Estimate 29
2.6.5. Asymptotic Properties of the Estimate 30
2.6.6. Classical Model Validation Tools 33
2.6.7. Closed-loop Identification 36
2.6.8. Data Preprocessing 37
2.7. Balanced Truncation 38
2.7.1. The Concepts of Controllability and Observability 38
2.7.2. Balanced Realisation of a System 40
2.7.3. Balanced Truncation 42
2.7.4. Numerical Issues 42
2.7.5. Frequency-weighted Balanced Truncation 43
2.7.6. Balanced Truncation of Discrete-time Systems 45

Chapter 3. Identification in Closed Loop for Better Control Design 47
3.1. Introduction 47
3.2. The Role of Feedback 48
3.3. The Effect of Feedback on the Modelling Errors 51
3.3.1. The Effect of Feedback on the Bias Error 51
3.3.2. The Effect of Feedback on the Variance Error 54
3.4. The Effect of Model Reduction on the Modelling Errors 56
3.4.1. Using Model Reduction to Tune the Bias Error 57
3.4.2. Dealing with the Variance Error 57
3.5. Summary of the Chapter 62

Chapter 4. Dealing with Controller Singularities in Closed-loop Identification 65

4.1. Introduction 65

4.2. The Importance of Nominal Closed-loop Stability for Control Design 66

4.3. Poles and Zeroes of a System 67

4.4. Loss of Nominal Closed-loop Stability with Unstable or Nonminimum-phase Controllers 69

4.4.1. The Indirect Approach 70

4.4.2. The Coprime-factor Approach 72

4.4.3. The Direct Approach 76

4.4.4. The Dual Youla Parametrisation Approach 78

4.5. Guidelines for an Appropriate Closed-loop Identification Experiment Design 80

4.5.1. Guidelines for the Choice of an Identification Method 80

4.5.2. Remark on High-order Models Obtained by Two-stage Methods 81

4.6. Numerical Illustration 82

4.6.1. Problem Description 82

4.6.2. The Indirect Approach 84

4.6.3. The Coprime-factor Approach 87

4.6.4. The Direct Approach 94

4.6.5. The Dual Youla Parametrisation Approach 98

4.6.6. Comments on the Numerical Example 107

4.7. Summary of the Chapter 110

Chapter 5. Model and Controller Validation for Robust Control in a Prediction-error Framework 111

5.1. Introduction 111

5.1.1. The Questions of the Cautious Process Control Engineer 111

5.1.2. Some Answers to these Questions 112

5.2. Model Validation Using Prediction-error Identification 116

5.2.1. Model Validation Using Open-loop Data 117

5.2.2. Control-oriented Model Validation Using Closed-loop Data 122

5.2.3. A Unified Representation of the Uncertainty Zone 128

5.3. Model Validation for Control and Controller Validation 129

5.3.1. A Control-oriented Measure of the Size of a Prediction-error Uncertainty Set 129
5.3.2. Controller Validation for Stability 132
5.3.3. Controller Validation for Performance 134
5.4. The Effect of Overmodelling on the Variance of Estimated Transfer Functions 137
5.4.1. The Effect of Superfluous Poles and Zeroes 137
5.4.2. The Choice of a Model Structure 140
5.5. Case Studies 142
5.5.1. Case Study I: Flexible Transmission System 142
5.5.2. Case Study II: Ferrosilicon Production Process 148
5.6. Summary of the Chapter 156

Chapter 6. Control-oriented Model Reduction and Controller Reduction 159
6.1. Introduction 159
6.1.1. From High to Low Order for Implementation Reasons 159
6.1.2. High-order Controllers 160
6.1.3. Contents of this Chapter 161
6.2. A Closed-loop Criterion for Model or Controller Order Reduction 161
6.3. Choice of the Reduction Method 164
6.4. Model Order Reduction 165
6.4.1. Open-loop Plant Coprime-factor Reduction 166
6.4.2. Performance-preserving Closed-loop Model Reduction 170
6.4.3. Stability-preserving Closed-loop Model Reduction 177
6.4.4. Preservation of Stability and Performance by Closed-loop Model Reduction 181
6.5. Controller Order Reduction 182
6.5.1. Open-loop Controller Coprime-factor Reduction 183
6.5.2. Performance-preserving Closed-loop Controller Reduction 184
6.5.3. Stability-preserving Closed-loop Controller Reduction 192
6.5.4. Other Closed-loop Controller Reduction Methods 195
6.6. Case Study: Design of a Low-order Controller for a PWR Nuclear Power Plant Model 196
6.6.1. Description of the System 196
6.6.2. Control Objective and Design 197
6.6.3. System Identification 199
6.6.4. Model Reduction 201

6.6.5. Controller Reduction 203
6.6.6. Performance Analysis of the Designed Controllers 204
6.7. Classification of the Methods and Concluding Remarks 207
6.8. Summary of the Chapter 208

Chapter 7. Some Final Words 211
7.1. A Unified Framework 211
7.2. Missing Links and Perspectives 212
7.3. Model-free Control Design 213

References 215

Index 223