Contents

Part I Introduction to Adaptive and Robust Active Vibration Control

1 Introduction to Adaptive and Robust Active Vibration Control 3
1.1 Active Vibration Control: Why and How 3
1.2 A Conceptual Feedback Framework 9
1.3 Active Damping 11
1.4 The Robust Regulation Paradigm 11
1.5 The Adaptive Regulation Paradigm 12
1.6 Concluding Remarks 14
1.7 Notes and Reference 15
References 15

2 The Test Benches 19
2.1 An Active Hydraulic Suspension System Using Feedback Compensation 19
2.2 An Active Vibration Control System Using Feedback Compensation Through an Inertial Actuator 22
2.3 An Active Distributed Flexible Mechanical Structure with Feedforward–Feedback Compensation 24
2.4 Concluding Remarks 27
2.5 Notes and References 28
References 28

Part II Techniques for Active Vibration Control

3 Active Vibration Control Systems—Model Representation 31
3.1 System Description 31
3.1.1 Continuous-Time Versus Discrete-Time Dynamical Models 31
3.1.2 Digital Control Systems 32
3.1.3 Discrete-Time System Models for Control 34
3.2 Concluding Remarks 37
3.3 Notes and References 37
References 37

4 Parameter Adaptation Algorithms 39
4.1 Introduction 39
4.2 Structure of the Adjustable Model 40
4.2.1 Case (a): Recursive Configuration for System Identification—Equation Error 40
4.2.2 Case (b): Adaptive Feedforward Compensation—Output Error 42
4.3 Basic Parameter Adaptation Algorithms 44
4.3.1 Basic Gradient Algorithm 44
4.3.2 Improved Gradient Algorithm 47
4.3.3 Recursive Least Squares Algorithm 52
4.3.4 Choice of the Adaptation Gain 57
4.3.5 An Example 61
4.4 Stability of Parameter Adaptation Algorithms 62
4.4.1 Equivalent Feedback Representation of the Adaptive Predictors 63
4.4.2 A General Structure and Stability of PAA 66
4.4.3 Output Error Algorithms—Stability Analysis 70
4.5 Parametric Convergence 72
4.5.1 The Problem 72
4.6 The LMS Family of Parameter Adaptation Algorithms 76
4.7 Concluding Remarks 77
4.8 Notes and References 78
References 78

5 Identification of the Active Vibration Control Systems—The Bases 81
5.1 Introduction 81
5.2 Input–Output Data Acquisition and Preprocessing 83
5.2.1 Input–Output Data Acquisition Under an Experimental Protocol 83
5.2.2 Pseudorandom Binary Sequences (PRBS) 83
5.2.3 Data Preprocessing 85

5.3 Model Order Estimation from Data. 86
5.4 Parameter Estimation Algorithms 88
5.4.1 Recursive Extended Least Squares (RELS) 90
5.4.2 Output Error with Extended Prediction Model (XOLOE) 92
5.5 Validation of the Identified Models. 94
5.5.1 Whiteness Test. 94
5.6 Concluding Remarks. 96
5.7 Notes and References 97
References 97

6 Identification of the Test Benches in Open-Loop Operation 99
6.1 Identification of the Active Hydraulic Suspension in Open-Loop Operation 99
6.1.1 Identification of the Secondary Path 100
6.1.2 Identification of the Primary Path 105
6.2 Identification of the AVC System Using Feedback Compensation Through an Inertial Actuator. 106
6.2.1 Identification of the Secondary Path 106
6.2.2 Identification of the Primary Path 112
6.3 Identification of the Active Distributed Flexible Mechanical Structure Using Feedforward–Feedback Compensation 113
6.4 Concluding Remarks. 119
6.5 Notes and References 119
References 119

7 Digital Control Strategies for Active Vibration Control—The Bases 121
7.1 The Digital Controller. 121
7.2 Pole Placement 123
7.2.1 Choice of H_R and H_S—Examples 124
7.2.2 Internal Model Principle (IMP). 126
7.2.3 Youla–Kučera Parametrization 127
7.2.4 Robustness Margins 129
7.2.5 Model Uncertainties and Robust Stability 132
7.2.6 Templates for the Sensitivity Functions 134
7.2.7 Properties of the Sensitivity Functions. 134
7.2.8 Input Sensitivity Function 137
7.2.9 Shaping the Sensitivity Functions for Active Vibration Control 139
7.3 Real-Time Example: Narrow-Band Disturbance Attenuation on the Active Vibration Control System Using an Inertial Actuator 143
7.4 Pole Placement with Sensitivity Function Shaping by Convex Optimisation 146

7.5 Concluding Remarks. 149
7.6 Notes and References 149
References 150

8 Identification in Closed-Loop Operation 153
8.1 Introduction. 153
8.2 Closed-Loop Output Error Identification Methods. 154
8.2.1 The Closed-Loop Output Error Algorithm 158
8.2.2 Filtered and Adaptive Filtered Closed-Loop Output Error Algorithms (F-CLOE, AF-CLOE). 159
8.2.3 Extended Closed-Loop Output Error Algorithm (X-CLOE) 160
8.2.4 Taking into Account Known Fixed Parts in the Model 161
8.2.5 Properties of the Estimated Model 162
8.2.6 Validation of Models Identified in Closed-Loop Operation 163
8.3 A Real-Time Example: Identification in Closed-Loop and Controller Redesign for the Active Control System Using an Inertial Actuator 165
8.4 Concluding Remarks. 169
8.5 Notes and References 169
References 170

9 Reduction of the Controller Complexity 171
9.1 Introduction. 171
9.2 Criteria for Direct Controller Reduction. 173
9.3 Estimation of Reduced Order Controllers by Identification in Closed-Loop 175
9.3.1 Closed-Loop Input Matching (CLIM) 175
9.3.2 Closed-Loop Output Matching (CLOM) 178
9.3.3 Taking into Account the Fixed Parts of the Nominal Controller. 178
9.4 Real-Time Example: Reduction of Controller Complexity 180
9.5 Concluding Remarks. 183
9.6 Notes and References 184
References 184

Part III Active Damping

10 Active Damping. 187
10.1 Introduction. 187
10.2 Performance Specifications 188
10.3 Controller Design by Shaping the Sensitivity Functions Using Convex Optimization. 192

10.4 Identification in Closed-Loop of the Active Suspension Using the Controller Designed on the Model Identified in Open-Loop 195
10.5 Redesign of the Controller Based on the Model Identified in Closed Loop 196
10.6 Controller Complexity Reduction 198
10.6.1 CLOM Algorithm with Simulated Data 200
10.6.2 Real-Time Performance Tests for Nominal and Reduced Order Controllers. 202
10.7 Design of the Controller by Shaping the Sensitivity Function with Band-Stop Filters 203
10.8 Concluding Remarks. 208
10.9 Notes and References 209
References 210

Part IV Feedback Attenuation of Narrow-Band Disturbances

11 Robust Controller Design for Feedback Attenuation of Narrow-Band Disturbances 213
11.1 Introduction. 213
11.2 System Description. 214
11.3 Robust Control Design 216
11.4 Experimental Results 219
11.4.1 Two Time-Varying Tonal Disturbances 220
11.4.2 Attenuation of Vibrational Interference 222
11.5 Concluding Remarks. 223
11.6 Notes and References 223
References 224

12 Direct Adaptive Feedback Attenuation of Narrow-Band Disturbances 225
12.1 Introduction. 225
12.2 Direct Adaptive Feedback Attenuation of Unknown and Time-Varying Narrow-Band Disturbances 226
12.2.1 Introduction 226
12.2.2 Direct Adaptive Regulation Using Youla–Kučera Parametrization. 230
12.2.3 Robustness Considerations. 232
12.3 Performance Evaluation Indicators for Narrow-Band Disturbance Attenuation 233
12.4 Experimental Results: Adaptive Versus Robust 236
12.4.1 Central Controller for Youla–Kučera Parametrization. 236
12.4.2 Two Single-Mode Vibration Control 236
12.4.3 Vibrational Interference 239

12.5 Adaptive Attenuation of an Unknown Narrow-Band Disturbance on the Active Hydraulic Suspension 241
12.6 Adaptive Attenuation of an Unknown Narrow-Band Disturbance on the Active Vibration Control System Using an Inertial Actuator 244
12.6.1 Design of the Central Controller 245
12.6.2 Real-Time Results 247
12.7 Other Experimental Results 249
12.8 Concluding Remarks 249
12.9 Notes and References 250
References 251

13 Adaptive Attenuation of Multiple Sparse Unknown and Time-Varying Narrow-Band Disturbances 255
13.1 Introduction 255
13.2 The Linear Control Challenge 255
13.2.1 Attenuation of Multiple Narrow-Band Disturbances Using Band-Stop Filters 257
13.2.2 IMP with Tuned Notch Filters 261
13.2.3 IMP Design Using Auxiliary Low Damped Complex Poles 262
13.3 Interlaced Adaptive Regulation Using Youla–Kučera IIR Parametrization 263
13.3.1 Estimation of A_Q 265
13.3.2 Estimation of $B_Q(q^{-1})$ 267
13.4 Indirect Adaptive Regulation Using Band-Stop Filters 271
13.4.1 Basic Scheme for Indirect Adaptive Regulation 272
13.4.2 Reducing the Computational Load of the Design Using the Youla–Kučera Parametrization 273
13.4.3 Frequency Estimation Using Adaptive Notch Filters 274
13.4.4 Stability Analysis of the Indirect Adaptive Scheme 277
13.5 Experimental Results: Attenuation of Three Tonal Disturbances with Variable Frequencies 277
13.6 Experimental Results: Comparative Evaluation of Adaptive Regulation Schemes for Attenuation of Multiple Narrow-Band Disturbances 278
13.6.1 Introduction 278
13.6.2 Global Evaluation Criteria 283
13.7 Concluding Remarks 290
13.8 Notes and References 290
References 291

Part V Feedforward-Feedback Attenuation of Broad-Band Disturbances

14 Design of Linear Feedforward Compensation of Broad-band Disturbances from Data 295
14.1 Introduction 295
14.2 Indirect Approach for the Design of the Feedforward Compensator from Data 298
14.3 Direct Approach for the Design of the Feedforward Compensator from Data 298
14.4 Direct Estimation of the Feedforward Compensator and Real-Time Tests 302
14.5 Concluding Remark 308
14.6 Notes and References 308
References 309

15 Adaptive Feedforward Compensation of Disturbances 311
15.1 Introduction 311
15.2 Basic Equations and Notations 314
15.3 Development of the Algorithms 316
15.4 Analysis of the Algorithms 319
15.4.1 The Perfect Matching Case 319
15.4.2 The Case of Non-perfect Matching 321
15.4.3 Relaxing the Positive Real Condition 323
15.5 Adaptive Attenuation of Broad-band Disturbances—Experimental Results 324
15.5.1 Broad-band Disturbance Rejection Using Matrix Adaptation Gain 325
15.5.2 Broad-band Disturbance Rejection Using Scalar Adaptation Gain 329
15.6 Adaptive Feedforward Compensation with Filtering of the Residual Error 336
15.7 Adaptive Feedforward + Fixed Feedback Compensation of Broad-band Disturbances 338
15.7.1 Development of the Algorithms 340
15.7.2 Analysis of the Algorithms 342
15.8 Adaptive Feedforward + Fixed Feedback Attenuation of Broad-band Disturbances—Experimental Results 343
15.9 Concluding Remarks 345
15.10 Notes and References 345
References 346

16 Youla–Kučera Parametrized Adaptive Feedforward Compensators 351
16.1 Introduction 351
16.2 Basic Equations and Notations 352

16.3 Development of the Algorithms 354
16.4 Analysis of the Algorithms 357
16.4.1 The Perfect Matching Case 357
16.4.2 The Case of Non-perfect Matching 358
16.4.3 Relaxing the Positive Real Condition 359
16.4.4 Summary of the Algorithms 359
16.5 Experimental Results 361
16.5.1 The Central Controllers and Comparison Objectives 361
16.5.2 Broad-band Disturbance Rejection Using Matrix Adaptation Gain 361
16.5.3 Broad-band Disturbance Rejection Using Scalar Adaptation Gain 364
16.6 Comparison of the Algorithms 366
16.7 Concluding Remarks. 368
16.8 Notes and References 368
References 368

Appendix A: Generalized Stability Margin and Normalized Distance Between Two Transfer Functions 371

Appendix B: Implementation of the Adaptation Gain Updating—The U-D Factorization 375

Appendix C: Interlaced Adaptive Regulation: Equations Development and Stability Analysis 377

Appendix D: Error Equations for Adaptive Feedforward Compensation. 381

Appendix E: "Integral + Proportional" Parameter Adaptation Algorithm. 389

Index 395

http://www.springer.com/978-3-319-41449-2

Adaptive and Robust Active Vibration Control
Methodology and Tests
Landau, I.D.; Airimițoaie, T.-B.; Castellanos-Silva, A.; Constantinescu, A.
2017, XXIV, 396 p. 219 illus., 37 illus. in color. With online files/update., Hardcover
ISBN: 978-3-319-41449-2