## 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
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part II</td>
<td>3</td>
<td>Active Vibration Control Systems—Model Representation</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>System Description</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>3.1.1</td>
<td>Continuous-Time Versus Discrete-Time Dynamical Models</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>3.1.2</td>
<td>Digital Control Systems</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>3.1.3</td>
<td>Discrete-Time System Models for Control</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>Concluding Remarks</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>Notes and References</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Parameter Adaptation Algorithms</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>Introduction</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>Structure of the Adjustable Model</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>4.2.1</td>
<td>Case (a): Recursive Configuration for System Identification—Equation Error</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>4.2.2</td>
<td>Case (b): Adaptive Feedforward Compensation—Output Error</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>4.3</td>
<td>Basic Parameter Adaptation Algorithms</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>4.3.1</td>
<td>Basic Gradient Algorithm</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>4.3.2</td>
<td>Improved Gradient Algorithm</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>4.3.3</td>
<td>Recursive Least Squares Algorithm</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>4.3.4</td>
<td>Choice of the Adaptation Gain</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>4.3.5</td>
<td>An Example</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>Stability of Parameter Adaptation Algorithms</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>4.4.1</td>
<td>Equivalent Feedback Representation of the Adaptive Predictors</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>4.4.2</td>
<td>A General Structure and Stability of PAA</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>4.4.3</td>
<td>Output Error Algorithms—Stability Analysis</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>Parametric Convergence</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>4.5.1</td>
<td>The Problem</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>The LMS Family of Parameter Adaptation Algorithms</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>Concluding Remarks</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>Notes and References</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Identification of the Active Vibration Control Systems—The Bases</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td>Introduction</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>Input–Output Data Acquisition and Preprocessing</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>5.2.1</td>
<td>Input–Output Data Acquisition Under an Experimental Protocol</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>5.2.2</td>
<td>Pseudorandom Binary Sequences (PRBS)</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>5.2.3</td>
<td>Data Preprocessing</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>
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
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
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
Adaptive and Robust Active Vibration Control
Methodology and Tests
Landau, I.D.; Airimiţoaie, 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