Wodek K. Gawronski

Dynamics and Control of Structures

A Modal Approach

With 126 Figures

Springer

Contents

Preface vii

List of Symbols xvii

PART 1. DYNAMICS

Chapter 1 Introduction 3

1.1 Flexible Structure Definition 3
1.2 Examples 4
1.2.1 A Simple Structure 5
1.2.2 A 2D Truss 5
1.2.3 A 3D Truss 6
1.2.4 The Deep Space Network Antenna 6
1.2.5 The International Space Station Structure 9

Chapter 2 Models 11

2.1 Models of a Linear System 12
2.2 Second-Order Structural Models 13
2.2.1 Nodal Models 13
2.2.2 Modal Models 14
2.3 State-Space Structural Models 19
2.3.1 Nodal Models 19
2.3.2 Modal Models 20
2.4 Models with Small Nonproportional Damping 27

Chapter 3 Controllability and Observability 32

3.1 Definition 32
3.2 Balanced Representation 35
3.3 Balanced Systems with Integrators 35
3.4 Structural Properties 36
3.4.1 The State-Space Modal Model 37
3.4.2 The Second-Order Modal Model 46
3.5 Three Ways to Compute Hankel Singular Values 51

Chapter 4 Norms **53**
4.1 Definition 53
4.1.1 The H_2 Norm 53
4.1.2 The H_∞ Norm 54
4.1.3 The Hankel Norm 54
4.2 Properties 55
4.2.1 The H_2 Norm 55
4.2.2 The H_∞ Norm 63
4.2.3 The Hankel Norm 66

Chapter 5 Model Reduction **70**
5.1 Reduction Through Truncation 71
5.2 Reduction Errors 72
5.2.1 H_2 Model Reduction 72
5.2.2 H_∞ and Hankel Model Reduction 73
5.3 Systems with Integrators 74
5.4 Structures with Actuators and Sensors 78
5.4.1 Actuators and Sensors in a Cascade Connection 79
5.4.2 Accelerometers as Sensors 81
5.4.3 Proof-Mass Actuators 82
5.4.4 Centrifugal Actuators 87

Chapter 6 Assignment **90**
6.1 Problem Statement 90
6.2 Algorithms 91
6.3 Uniformly Balanced Systems 95

Chapter 7 Actuator and Sensor Placement **100**
7.1 Problem Statement 101
7.2 Additive Property of Modal Norms 101
7.2.1 The H_2 Norm 101
7.2.2 The H_∞ and Hankel Norms 102
7.3 Placement Indices and Matrices 103
7.3.1 H_2 Placement Indices and Matrices 103
7.3.2 H_∞ and Hankel Placement Indices and Matrices 105
7.3.3 Actuator/Sensor Indices and Modal Indices 106
7.4 Placement for Large Structures 110
7.4.1 Actuator Placement Strategy 111
7.4.2 Sensor Placement Strategy 111
7.5 Placement for General Plant Configuration 116
7.5.1 Structural Testing and Control 116
7.5.2 Properties 119
7.5.3 Placement Indices and Matrices 123

PART 2. CONTROL

Chapter 8 Dissipative Controllers **131**

8.1 Definition and Properties 131
8.2 Dissipative Controllers for Flexible Structures 133
8.3 Design Examples 138
8.3.1 A Simple Structure 138
8.3.2 The 2D Truss 140

Chapter 9 LQG Controllers **142**

9.1 Definition and Gains 143
9.2 Balanced LQG Controller 145
9.3 Weights of Special Interest 146
9.4 Low-Authority LQG Controller 148
9.5 Approximate Solutions of CARE and FARE 150
9.6 Almost-LQG-Balanced Modal Representation 156
9.7 Three Ways to Compute LQG Singular Values 157
9.8 Tracking LQG Controller 157
9.9 Frequency Weighting 160
9.10 Reduced-Order LQG Controller 162
9.10.1 The Reduction Index 162
9.10.2 The Reduction Technique 164
9.10.3 Stability of the Reduced-Order Controller 165
9.10.4 Performance of the Reduced-Order Controller 167
9.11 Design Examples 168
9.11.1 A Simple Structure 168
9.11.2 The 3D Truss 170
9.11.3 The 3D Truss with Input Filter 172
9.11.4 The Deep Space Network Antenna 174

Chapter 10 H_∞ and H_2 Controllers **177**

10.1 Definition and Gains 178
10.2 The Balanced H_∞ Controller 180
10.3 The H_2 Controller 183
10.4 The Balanced H_2 Controller 184
10.5 The Low-Authority H_∞ Controller 185
10.6 Approximate Solutions of HCARE and HFARE 187
10.7 Almost-H_∞-Balanced Modal Representation 189
10.8 Three Ways to Compute H_∞ Singular Values 189
10.9 Tracking H_∞ Controller 190
10.10 Frequency Weighting 190
10.11 The Closed-Loop System 193
10.12 The Reduced-Order H_∞ Controller 194

10.12.1 The Reduction Index 194
10.12.2 Closed-Loop Poles 195
10.12.3 Controller Performance 196
10.13 Design Examples 197
10.13.1 A Simple Structure 197
10.13.2 The 2D Truss 200
10.13.3 Filter Implementation Example 203
10.13.4 The Deep Space Network Antenna with Wind Disturbance Rejection Properties 203

Appendix A Matlab Functions 206
A.1 Transformation to the Modal Representation 206
A.2 Open-Loop Balanced Representation 207
A.3 H_2 Modal Norm 208
A.4 H_∞ Modal Norm 208
A.5 Hankel Modal Norm 209
A.6 LQG Balanced Representation 210
A.7 H_∞ Balanced Representation 211

Appendix B Structural Parameters 213
B.1 Stiffness and Mass Matrices of the 2D Truss 213
B.2 State-Space Representation of the Deep Space Network Antenna 215

References 217

Index 227