

Contents

About the Authors	xi
Preface	xiii
Acknowledgements	xv
1 Active Damping	1
1.1 Introduction	1
1.1.1 <i>Why Suppress Vibrations?</i>	1
1.1.2 <i>How can Vibrations be Reduced?</i>	2
1.2 Structural Control	2
1.3 Plant Description	3
1.3.1 <i>Error Budget</i>	4
1.4 Equations of Structural Dynamics	6
1.4.1 <i>Equation of Motion Including Seismic Excitation</i>	6
1.4.2 <i>Modal Coordinates</i>	8
1.4.3 <i>Support Reaction, Dynamic Mass</i>	10
1.4.4 <i>Dynamic Flexibility Matrix</i>	12
1.5 Collocated Control System	15
1.5.1 <i>Transmission Zeros and Constrained System</i>	18
1.5.2 <i>Nearly Collocated Control System</i>	20
1.5.3 <i>Non-Collocated Control Systems</i>	21
1.6 Active Damping with Collocated System	24
1.6.1 <i>Lead Control</i>	25
1.6.2 <i>Direct Velocity Feedback</i>	29
1.6.3 <i>Positive Position Feedback</i>	31
1.6.4 <i>Integral Force Feedback</i>	35
1.6.5 <i>Duality between The Lead and IFF Controllers</i>	44
1.7 Decentralized Control with Collocated Pairs	46
1.7.1 <i>Cross-Talk</i>	46
1.7.2 <i>Transmission Zeros (Case 1)</i>	47
1.7.3 <i>Transmission Zeros (Case 2)</i>	52
References	55

vi Contents

2	Active Isolation	57
2.1	Introduction	57
2.2	Relaxation Isolator	60
2.2.1	<i>Electromagnetic Realization</i>	62
2.3	Sky-hook Damper	64
2.4	Force Feedback	66
2.5	Six-Axis Isolator	69
2.5.1	<i>Decentralized Control</i>	73
2.5.2	<i>Leg Design</i>	76
2.5.3	<i>Model of the Isolator</i>	80
2.5.4	<i>Six-Axis Transmissibility</i>	82
2.6	Vehicle Active Suspension	89
2.6.1	<i>Quarter-Car Model</i>	91
2.7	Semi-Active Suspension	106
2.7.1	<i>Semi-Active Devices</i>	106
2.7.2	<i>Narrow-Band Disturbance</i>	107
2.7.3	<i>Quarter-Car Semi-Active Suspension</i>	108
	References	113
3	A Comparison of Passive, Active and Hybrid Control	117
3.1	Introduction	117
3.2	System Description	119
3.3	The Dynamic Vibration Absorber	120
3.3.1	<i>Single-d.o.f. Oscillator</i>	120
3.3.2	<i>Multiple-d.o.f. System</i>	123
3.3.3	<i>Shear Frame Example</i>	124
3.4	Active Mass Damper	126
3.5	Hybrid Control	131
3.6	Shear Control	133
3.7	Force Actuator, Displacement Sensor	135
3.7.1	<i>Direct Velocity Feedback</i>	136
3.7.2	<i>First-Order Positive Position Feedback</i>	137
3.7.3	<i>Comparison of the DVF and the PPF</i>	138
3.8	Displacement Actuator, Force Sensor	140
3.8.1	<i>Comparison of the IFF and the DVF</i>	142
	References	144
4	Vibration Control Methods and Devices	147
4.1	Introduction	147
4.2	Classification of Vibration Control Methods	148

4.3	Construction of Active Dynamic Absorber	151
4.4	Control Devices for Wind Excitation Control in Civil Structures	154
4.5	Real Towers Using the Connected Control Method	156
4.6	Application of Active Dynamic Absorber for Controlling Vibration of Single-d.o.f. Systems	158
4.6.1	<i>Equations of Motion and State Equation</i>	159
4.6.2	<i>Representation of a Non-Dimensional State Equation</i>	160
4.6.3	<i>Control System Design</i>	162
4.6.4	<i>Similarity Law between Dimensional and Non-dimensional System</i>	163
4.6.5	<i>Analysis of Vibration Control Effect</i>	165
4.6.6	<i>Experiment</i>	173
4.7	Remarks	175
	References	176
5	Reduced-Order Model for Structural Control	179
5.1	Introduction	179
5.2	Modeling of Distributed Structures	180
5.2.1	<i>Equation of Motion for Distributed Structures</i>	180
5.2.2	<i>Conventional Modeling of Structures</i>	181
5.3	Spillover	183
5.4	The Lumped Modeling Method	185
5.4.1	<i>A Key Idea for Deriving a Reduced-Order Model</i>	185
5.4.2	<i>Relationship Between Physical and Modal Coordinate Systems</i>	187
5.4.3	<i>Modification of Normalized Modal Matrix</i>	188
5.5	Method of Equivalent Mass Estimation	190
5.5.1	<i>Meaning of Equivalent Mass</i>	190
5.5.2	<i>Eigenvector Method</i>	191
5.5.3	<i>Mass Response Method</i>	193
5.6	Modeling of Tower-like Structure	197
5.6.1	<i>Two-d.o.f. Model</i>	197
5.6.2	<i>Dimension and Dynamic Characteristics of the Tower-Like Structure</i>	198
5.6.3	<i>Calculation of Parameters of Two-d.o.f. Model</i>	201
5.6.4	<i>Comparison between the Distributed Parameter and Two-d.o.f. Systems</i>	203

viii Contents

5.7	Modeling of Plate Structures	203
5.7.1	<i>Dimensions of a Plate Structure</i>	203
5.7.2	<i>Three-d.o.f. Model</i>	206
5.7.3	<i>Calculation of Parameters of the Three-d.o.f. Model</i>	207
5.7.4	<i>Comparison between Real System and Three-d.o.f. Systems</i>	208
5.8	Modeling of a Bridge Tower	209
5.8.1	<i>Dimensions of a Scaled Bridge Tower</i>	209
5.8.2	<i>Construction of a Four-d.o.f. Model</i>	210
5.8.3	<i>Calculation of Parameters of the Four-d.o.f. Model</i>	212
5.8.4	<i>Comparison between Real System and Four-d.o.f. Systems</i>	213
5.9	Robust Vibration Control for Neglected Higher Modes	217
5.10	Conclusions	217
	References	219
6	Active Control of Civil Structures	221
6.1	Introduction	221
6.2	Classification of Structural Control for Buildings	222
6.3	Modeling and Vibration Control for Tower Structures	222
6.3.1	<i>One-d.o.f. Model</i>	222
6.3.2	<i>Two-d.o.f. Model for Tower-Like Structures and Its LQ Control</i>	225
6.3.3	<i>Three-d.o.f. Model for Broad Structures and Its H_∞ Robust Control</i>	228
6.3.4	<i>Four-d.o.f. Model for Bridge Tower and Spillover Suppression Using Filtered LQ Control</i>	239
6.4	Active Vibration Control of Multiple Buildings Connected with Active Control Bridges in Response to Large Earthquakes	249
6.4.1	<i>Construction of Four Model Buildings</i>	249
6.4.2	<i>Characteristics of the Tower Structures</i>	251
6.4.3	<i>Reduced-order Model of the Four Tower Structures Connected by Four Actuators</i>	252
6.4.4	<i>Control System Design</i>	254
6.4.5	<i>Simulated Results of Seismic Response Control</i>	257
6.4.6	<i>Experiment</i>	259
6.5	Vibration Control for Real Triple Towers Using CCM	264
6.5.1	<i>Outline of the Triple Towers</i>	264
6.5.2	<i>Modeling of Towers</i>	265

6.5.3	<i>Control System Design</i>	266
6.5.4	<i>Simulation of the Triple Towers Using CCM</i>	269
6.5.5	<i>Realization of the CCM</i>	270
6.6	Vibration Control of Bridge Towers Using a Lumped Modeling Approach	274
6.6.1	<i>Vibration Problem of Bridge Towers Under Construction</i>	274
6.6.2	<i>Controlled Object and Its Dynamic Characteristics</i>	277
6.6.3	<i>Five-d.o.f. Modeling of a Scaled Bridge Tower Structure with a Crane Tower</i>	278
6.6.4	<i>LQ Control System Design</i>	278
6.6.5	<i>Simulations</i>	283
6.6.6	<i>Experiments</i>	283
6.6.7	<i>H_∞ Robust Control</i>	286
6.7	Conclusion	290
	References	291
	Index	293

