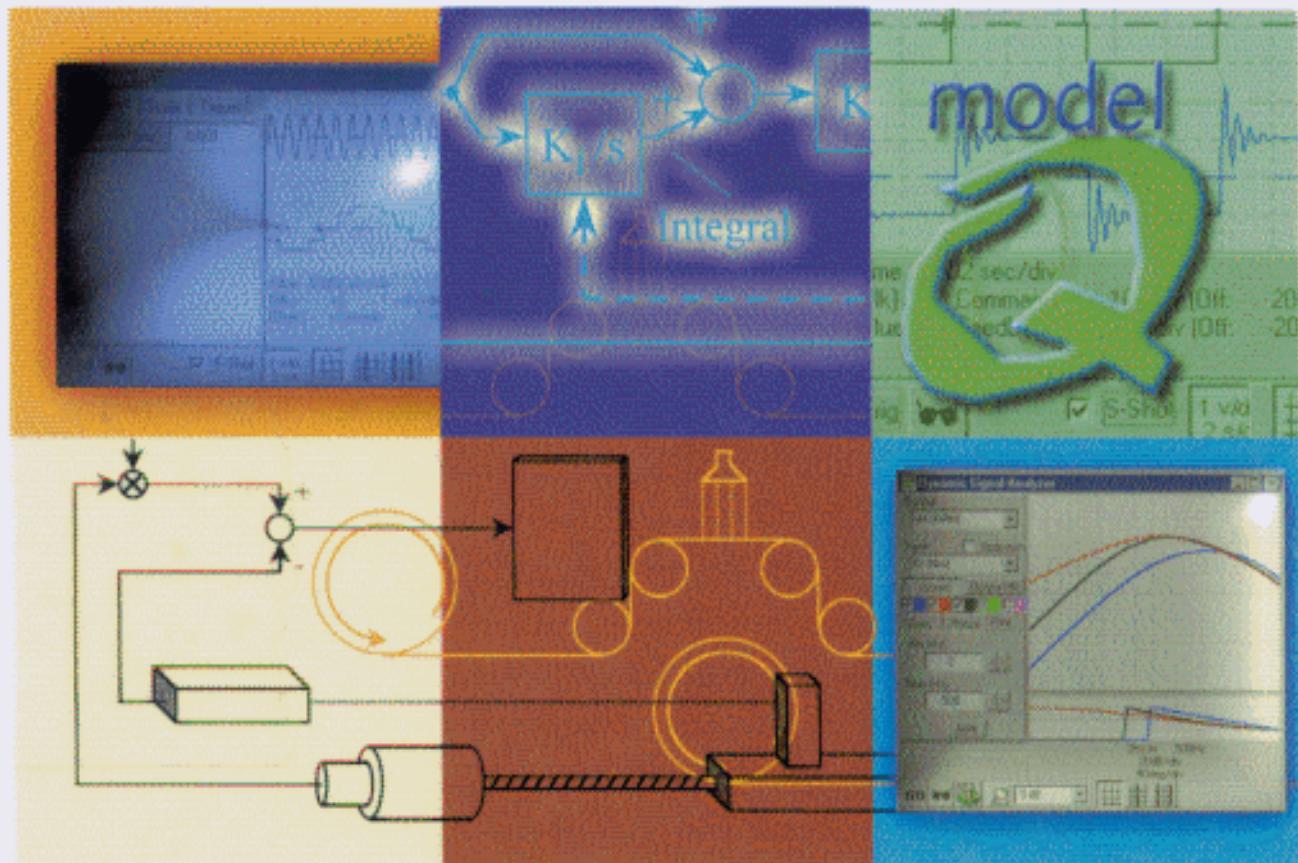


second edition

control system design guide

using your computer to understand
and diagnose feedback controllers



George Ellis

Contents

Foreword	xvii
Preface	xxi
Section 1 Applied Principles of Controls	1
Important Safety Guidelines for Readers	3
Chapter 1 Introduction to Controls	5
1.1 <i>ModelQ</i> Simulation Environment	6
<i>1.1.1 Installation of ModelQ</i>	6
<i>1.1.2 Errata</i>	7
1.2 The Control System	7
<i>1.2.1 The Controller</i>	7
<i>1.2.2 The Machine</i>	8
1.3 The Controls Engineer	8
Chapter 2 The Frequency Domain	11
2.1 The Laplace Transform	11
2.2 Transfer Functions	12
<i>2.2.1 What is s?</i>	13
<i>2.2.2 Linearity, Time Invariance, and Transfer Functions</i>	13
2.3 Examples of Transfer Functions	14

CONTENTS

2.3.1	<i>Transfer Functions of Controller Elements</i>	14
2.3.2	<i>Transfer Functions of Power Conversion</i>	16
2.3.3	<i>Transfer Functions of Physical Elements</i>	16
2.3.4	<i>Transfer Functions of Feedback</i>	19
2.4	<i>Block Diagrams</i>	19
2.4.1	<i>Combining Blocks</i>	20
2.5	<i>Phase and Gain</i>	21
2.5.1	<i>Phase and Gain from Transfer Functions</i>	23
2.5.2	<i>Bode Plots: Phase and Gain versus Frequency</i>	23
2.6	<i>Measuring Performance</i>	24
2.6.1	<i>Command Response</i>	25
2.6.2	<i>Stability</i>	27
2.6.3	<i>Time Domain versus Frequency Domain</i>	28
2.6.4	<i>Experiment 2-1: PI+ Controller</i>	29
 Chapter 3	 Tuning a Control System	31
3.1	<i>Closing Loops</i>	32
3.1.1	<i>The Source of Instability</i>	32
3.2	<i>A Detailed Review of the Model</i>	34
3.2.1	<i>Integrator</i>	35
3.2.2	<i>Power Converter</i>	36
3.2.3	<i>PI Control Law</i>	37
3.2.4	<i>Feedback Filter</i>	39
3.3	<i>The Open-Loop Method</i>	39
3.4	<i>Margins of Stability</i>	41
3.4.1	<i>Quantifying GM and PM</i>	42
3.4.2	<i>Experiment 3-1: Understanding the Open-Loop Method</i>	42
3.4.3	<i>Open Loop, Closed Loop, and the Step Response</i>	43
3.5	<i>A Zone-Based Tuning Procedure</i>	45
3.5.1	<i>Zone One: Proportional</i>	47
3.5.2	<i>Zone Two: Integral</i>	48
3.6	<i>Variation in Plant Gain</i>	49
3.6.1	<i>Accommodating Changing Gain</i>	50
3.7	<i>Multiple (Cascaded) Loops</i>	51
3.8	<i>Saturation and Synchronization</i>	52
3.8.1	<i>Avoid Saturation when Tuning</i>	55
 Chapter 4	 Delay in Digital Controllers	57
4.1	<i>How Sampling Works</i>	58

4.2	Sources of Delay in Digital Systems	59
4.2.1	<i>Sample-and-Hold Delay</i>	59
4.2.2	<i>Calculation Delay</i>	60
4.2.3	<i>Velocity Estimation</i>	61
4.2.4	<i>The Sum of the Delays</i>	61
4.3	Experiment 4-1: Understanding Delay in Digital Control	62
4.3.1	<i>Tuning the Controller</i>	63
4.4	Selecting the Sample Time	65
4.4.1	<i>Aggressive Assumptions for General Systems</i>	65
4.4.2	<i>Aggressive Assumptions for Position-Based Motion Systems</i>	66
4.4.3	<i>Moderate and Conservative Assumptions</i>	67
Chapter 5	The z-Domain	69
5.1	Introduction to the z-Domain	69
5.1.1	<i>Definition of z</i>	69
5.1.2	<i>z-Domain Transfer Functions</i>	70
5.1.3	<i>Bilinear Transform</i>	70
5.2	z Phasors	72
5.3	Aliasing	73
5.4	Experiment 5-1: Aliasing	75
5.4.1	<i>Bode Plots and Block Diagrams in z</i>	77
5.4.2	<i>DC Gain</i>	77
5.5	From Transfer Function to Algorithm	78
5.6	Functions for Digital Systems	80
5.6.1	<i>Digital Integrals and Derivatives</i>	80
5.6.2	<i>Digital Derivatives</i>	83
5.6.3	<i>Sample-and-Hold</i>	87
5.6.4	<i>DAC/ADC: Converting to and from Analog</i>	89
5.7	Reducing the Calculation Delay	90
5.8	Selecting a Processor	91
5.8.1	<i>Fixed- and Floating-Point Math</i>	91
5.8.2	<i>Overrunning the Sample Time</i>	93
5.8.3	<i>Other Algorithms</i>	93
5.8.4	<i>Ease of Programming</i>	93
5.8.5	<i>The Processor's Future</i>	93
5.8.6	<i>Making the Selection</i>	94
5.9	Quantization	94
5.9.1	<i>Limit Cycles and Dither</i>	95
5.9.2	<i>Offset and Limit Cycles</i>	97

Chapter 6	Six Types of Controllers	99
6.1	Tuning in This Chapter	100
6.2	Using the Proportional Gain	101
6.2.1	<i>P Control</i>	101
6.3	Using the Integral Gain	105
6.3.1	<i>PI Control</i>	105
6.3.2	<i>PI+ Control</i>	110
6.4	Using the Differential Gain	114
6.4.1	<i>PID Control</i>	115
6.5	<i>PID+ Control</i>	123
6.5.1	<i>How to Tune a PID+ Controller</i>	124
6.6	<i>PD Control</i>	126
6.6.1	<i>How to Tune a PD Controller</i>	127
6.7	Choosing the Controller	127
6.8	Experiment 6-1: PID Controller	129
Chapter 7	Disturbance Response	133
7.1	Disturbances	134
7.1.1	<i>Disturbance Response of a Power Supply</i>	137
7.2	Disturbance Response of a Velocity Controller	141
7.2.1	<i>Time Domain</i>	143
7.2.2	<i>Frequency Domain</i>	145
7.3	Disturbance Decoupling	147
7.3.1	<i>Applications for Disturbance Decoupling</i>	149
Chapter 8	Feed-Forward	159
8.1	Feed-Forward for the General System	160
8.1.1	<i>Nonideal Power Conversion and Feedback</i>	162
8.1.2	<i>Increasing the Bandwidth versus Feed-Forward Compensation</i>	166
8.1.3	<i>Imperfect Knowledge of the Plant</i>	167
8.1.4	<i>Overshoot to Nonsquare Waves</i>	169
8.2	Feed-Forward for the Double-Integrating Plant	170
8.3	Experiment 8-1: Feed-Forward	172
Chapter 9	Filters in Control Systems	175
9.1	Filters in Control Systems	176
9.1.1	<i>Filters in the Controller</i>	176
9.1.2	<i>Filters in the Power Converter</i>	179
9.1.3	<i>Filters in the Feedback</i>	179

9.2	Filter Passband	180.
9.2.1	<i>Low-Pass Filters</i>	180
9.2.2	<i>Notch</i>	186
9.3	Implementation of Filters	189
9.3.1	<i>Passive Analog Filters</i>	189
9.3.2	<i>Active Analog Filters</i>	190
9.3.3	<i>Switched Capacitor Filters</i>	190
9.3.4	<i>IIR Digital Filters</i>	190
9.3.5	<i>FIR Digital Filters</i>	194
Section II	Modeling	197
Chapter 10	Introduction to Modeling	199
10.1	What Is a Model?	200
10.2	Frequency-Domain Modeling	200
10.2.1	<i>How the Frequency Domain Works</i>	200
10.3	Time-Domain Modeling	202
10.3.1	<i>State Variables</i>	202
10.3.2	<i>The Modeling Environment</i>	205
10.3.3	<i>The Model</i>	208
10.3.4	<i>Frequency Information from Time-Domain Models</i>	219
Chapter 11	Nonlinear Behavior and Time Variation	221
11.1	LTI versus Non-LTI	221
11.2	Non-LTI Behavior	222
11.2.1	<i>Slow Variation</i>	222
11.2.2	<i>Fast Variation</i>	223
11.3	Dealing with Nonlinear Behavior	224
11.3.1	<i>Modify the Plant</i>	224
11.3.2	<i>Tuning for Worst Case</i>	225
11.3.3	<i>Compensate in the Controller ("Gain Scheduling")</i>	226
11.4	Ten Examples of Nonlinear Behavior	227
11.4.1	<i>Plant Saturation</i>	227
11.4.2	<i>Deadband</i>	230
11.4.3	<i>Reversal Shift</i>	232
11.4.4	<i>Variation of Apparent Inertia</i>	233
11.4.5	<i>Friction</i>	234
11.4.6	<i>Quantization</i>	239
11.4.7	<i>Deterministic Feedback Error</i>	239

CONTENTS

<i>11.4.8</i>	<i>Power Converter Saturation</i>	241
<i>11.4.9</i>	<i>Pulse Modulation</i>	243
<i>11.4.10</i>	<i>Hysteresis Controllers</i>	246
Chapter 12 Seven Steps to Developing a Model		249
<i>12.1</i>	Determine the Purpose of the Model	250
<i>12.1.1</i>	<i>Training</i>	250
<i>12.1.2</i>	<i>Troubleshooting</i>	250
<i>12.1.3</i>	<i>Testing</i>	251
<i>12.1.4</i>	<i>Predicting</i>	251
<i>12.2</i>	Model in SI Units	252
<i>12.3</i>	Identify the System	252
<i>12.3.1</i>	<i>Identifying the Plant</i>	253
<i>12.3.2</i>	<i>Identifying the Power Converter</i>	254
<i>12.3.3</i>	<i>Identifying the Feedback</i>	255
<i>12.3.4</i>	<i>Identifying the Controller</i>	256
<i>12.4</i>	Build the Block Diagram	256
<i>12.5</i>	Select Frequency or Time Domain	257
<i>12.6</i>	Write the Model Equations	257
<i>12.7</i>	Verify the Model	257
Section III Motion Control		259
Chapter 13 Encoders and Resolvers		261
<i>13.1</i>	Accuracy, Resolution, and Response	263
<i>13.2</i>	Encoders	264
<i>13.3</i>	Resolvers	265
<i>13.3.1</i>	<i>Software Resolver-to-Digital Converter</i>	266
<i>13.3.2</i>	<i>Resolver Error and Multispeed Resolvers</i>	267
<i>13.4</i>	Impact of Resolution on Velocity Estimation	269
<i>13.4.1</i>	<i>Higher Gain Generates More Noise</i>	270
<i>13.4.2</i>	<i>Filtering the Noise</i>	271
<i>13.4.3</i>	<i>Experiment 13-1: Resolution Noise</i>	273
<i>13.5</i>	Alternatives for Increasing Resolution	273
<i>13.5.1</i>	<i>The I/T Interpolation or Clock Pulse Counting Method</i>	273
<i>13.5.2</i>	<i>Sine Encoders</i>	275
<i>13.6</i>	Cyclic Error and Torque Ripple	276
<i>13.7</i>	Experiment 13-1 (Continued): Cyclic Errors and Torque Ripple	281
<i>13.7.1</i>	<i>Relationship between Error Magnitude and Ripple</i>	282

<i>13.7.2</i>	<i>Relationship between Velocity and Ripple</i>	283
<i>13.7.3</i>	<i>Relationship between Bandwidth and Ripple</i>	283
<i>13.7.4</i>	<i>Relationship between Inertia and Ripple</i>	283
<i>13.7.5</i>	<i>Effect of Filters</i>	284
<i>13.7.6</i>	<i>Effect of Changing the Error Harmonic</i>	284
<i>13.7.7</i>	<i>Effect of Raising Resolver Speed</i>	284
<i>13.8</i>	<i>Choosing a Feedback Device</i>	285
<i>13.8.1</i>	<i>Suppliers</i>	286
Chapter 14	Basics of the Electric Servomotor and Drive	289
<i>14.1</i>	<i>Definition of a Drive</i>	290
<i>14.2</i>	<i>Definition of a Servo System</i>	291
<i>14.3</i>	<i>Basic Magnetics</i>	292
<i>14.3.1</i>	<i>Electromagnetism</i>	295
<i>14.3.2</i>	<i>The Right-Hand Rule</i>	295
<i>14.3.3</i>	<i>Completing the Magnetic Path</i>	296
<i>14.4</i>	<i>Electric Servomotors</i>	297
<i>14.4.1</i>	<i>Torque Ratings</i>	298
<i>14.4.2</i>	<i>Rotary and Linear Motion</i>	299
<i>14.4.3</i>	<i>Linear Motors</i>	299
<i>14.5</i>	<i>Permanent-Magnet (PM) Brush Motors</i>	301
<i>14.5.1</i>	<i>Creating the Winding Flux</i>	302
<i>14.5.2</i>	<i>Commutation</i>	302
<i>14.5.3</i>	<i>Torque Production</i>	302
<i>14.5.4</i>	<i>Electrical Angle versus Mechanical Angle</i>	303
<i>14.5.5</i>	<i>K_T, the Motor Torque Constant</i>	305
<i>14.5.6</i>	<i>Back EMF</i>	306
<i>14.5.7</i>	<i>Control of PM Brush Motors</i>	307
<i>14.5.8</i>	<i>Brush Motor Strengths and Weaknesses</i>	310
<i>14.6</i>	<i>Brushless PM Motors</i>	311
<i>14.6.1</i>	<i>Windings of Brushless PM Motors</i>	312
<i>14.6.2</i>	<i>Sinusoidal Commutation</i>	312
<i>14.6.3</i>	<i>Phase Control of Brushless PM Motors</i>	314
<i>14.6.4</i>	<i>DQ Control of Brushless PM Motors</i>	321
<i>14.6.5</i>	<i>Comparing DQ and Phase Control</i>	324
<i>14.7</i>	<i>Six-Step Control of Brushless PM Motor</i>	326
<i>14.7.1</i>	<i>Sensing Position for Commutation</i>	327
<i>14.7.2</i>	<i>Comparison of Brush and Brushless Motors</i>	330
<i>14.8</i>	<i>Induction and Reluctance Motors</i>	330

Chapter 15	Compliance and Resonance	331
15.1	Equations of Resonance	333
15.1.1	<i>Resonance with Load Feedback</i>	335
15.2	High-Frequency and Low-Frequency Resonance	336
15.3	Curing Resonance	338
15.3.1	<i>Stiffen the Transmission</i>	339
15.3.2	<i>Add Damping</i>	340
15.3.3	<i>Increase Motor Inertia</i>	341
15.3.4	Filters	344
Chapter 16	Position Loops	351
16.1	Cascaded Position/Velocity Loops	351
16.1.1	<i>Feed-Forward in Cascaded Controllers</i>	352
16.1.2	<i>Tuning a Cascaded Controller</i>	355
16.2	PID Position Loops	358
16.2.1	<i>Tuning a PID Position Controller</i>	359
16.3	Comparing Position Loops	361
16.3.1	<i>Comparing Feed-Forward</i>	362
16.3.2	<i>Velocity versus Current Drive</i>	363
16.4	Dual-Loop Control	364
16.5	Frequency-Domain Measurements	365
16.5.1	<i>Using a DSA on a Digital System</i>	366
16.5.2	<i>Measuring PI Velocity Controllers</i>	366
16.5.3	<i>Factor in Velocity Sample Delay</i>	367
16.5.4	<i>Measuring PI+ Velocity Controllers</i>	368
16.5.5	<i>Measuring Cascaded Position Loops</i>	370
16.5.6	<i>Measuring PID Position Loops</i>	371
Appendix A	Active Analog Implementation of Controller Elements	375
	Integrator	375
	Differentiator	376
	Lag Compensator	377
	Lead Compensator	378
	Lead-Lag Compensator	379
	Sallen-and-Key Low-Pass Filter	380
	Adjustable Notch Filter	381

Appendix B European Symbols for Block Diagrams	383
Part I. Linear Functions	383
Part II. Nonlinear Functions	384
Appendix C The Runge-Kutta Method	387
The Runge-Kutta Algorithm	387
Basic Version of the Runge-Kutta Algorithm	388
C Programming Language Version of the Runge-Kutta Algorithm	390
Appendix D Development of the Bilinear Transformation	393
Bilinear Transformation	393
Prewarping	394
Factoring Polynomials	395
Phase Advancing	395
Appendix E Mason's Signal Flow Graph Rule	397
Signal Flow Graphs	397
Step-by-Step Procedure	398
Appendix F The Parallel Form of Digital Algorithms	401
Appendix G Basic Matrix Math	405
Matrix Summation	405
Matrix Multiplication	405
Matrix Scaling	406
Matrix Inversion	406
Appendix H Using <i>ModelQ</i> to Produce Figures	407
Appendix I Variables and Constants Used in Simulations	419
Experiment 2-1	419
Experiment 3-1	420
Experiment 4-1	421
Experiment 5-1	422
Experiment 5-2	422
Experiment 6-1	423
Experiment 7-1	425
Experiment 8-1	426

CONTENTS

Experiment 9-1	Reaction of Alkyl Halides with Zinc Chloride 38	427
Experiment 9-2	Alkyne Preparation 41	428
Experiment 13-1	Acid-Base Titration 47	429
Experiment 15-1	Redox Reactions 53	430
Experiment 16-1	Hydrogenation of Alkenes 60	432
Experiment 16-2	Preparation of Alkyl Ethers 67	433

References

Index