

Contents

Acknowledgements	xiii
1 Introduction	1
1.1 Targeted Readership	2
1.2 Motion System History	2
1.3 Suggested Library for Motion System Design Reference	5
	6
2 Control Theory Overview	7
2.1 Classic Differential/Integral Equation Approach	7
2.2 LaPlace Transform-the S Domain	10
2.3 The Transfer Function	13
2.4 Open versus Closed Loop Control	15
2.4.1 <i>Transient and Frequency Response</i>	18
2.5 Stability	22
2.6 Basic Mechanical and Electrical Systems	23
2.6.1 <i>Equations and Constants</i>	23
2.6.2 <i>Power Test</i>	26
2.6.3 <i>Retardation Test</i>	26
2.7 Sampled Data Systems/Digital Control	28
2.7.1 <i>Sampling</i>	28
2.7.2 <i>Quantization</i>	30
2.7.3 <i>Computational Delay</i>	30
2.7.4 <i>System Analysis</i>	31
References	34
3 System Components	35
3.1 Motors and Amplifiers	35
3.1.1 <i>Review of Motor Theory</i>	36
3.1.2 <i>The Brush Motor</i>	37
3.1.3 <i>The "H" Drive PWM Amplifier</i>	46
3.1.4 <i>The Brushless Motor</i>	48
3.1.5 <i>Speed/Torque Curves</i>	57
3.1.6 <i>Thermal Effects</i>	59

3.1.7	<i>Motor Constant</i>	72
3.1.8	<i>Linear Motor</i>	74
3.1.9	<i>Stepper Motors</i>	78
3.1.10	<i>Induction Motors</i>	97
3.2	Gearheads	107
3.2.1	<i>Spur Gearhead</i>	107
3.2.2	<i>Planetary Gearhead</i>	109
3.2.3	<i>Hybrid Gearhead</i>	110
3.2.4	<i>Worm Gearhead</i>	110
3.2.5	<i>Harmonic Gearhead</i>	110
3.2.6	<i>Gearhead Sizing – Continuous Operation</i>	111
3.2.7	<i>Gearhead Sizing – Intermittent Operation</i>	112
3.2.8	<i>Axial and Radial Load</i>	114
3.2.9	<i>Backlash and Stiffness</i>	114
3.2.10	<i>Temperature/Thermal Resistance</i>	116
3.2.11	<i>Planetary/Spur Gearhead Comparison</i>	118
3.3	Leadscrews and Ballscrews	119
3.3.1	<i>Leadscrew Specifications</i>	120
3.3.2	<i>Ball Screw Specifications</i>	120
3.3.3	<i>Critical Speed</i>	121
3.3.4	<i>Column Strength</i>	122
3.3.5	<i>Starts, Pitch, Lead</i>	124
3.3.6	<i>Encoder/Lead</i>	125
3.3.7	<i>Accuracy</i>	125
3.3.8	<i>Backdrive – Self-Locking</i>	125
3.3.9	<i>Assemblies</i>	125
3.4	Belt and Pulley	126
3.4.1	<i>Belt</i>	128
3.4.2	<i>Guidance/Alignment</i>	128
3.4.3	<i>Belt and Pulley versus Ball Screw</i>	129
3.5	Rack and Pinion	129
3.5.1	<i>Design Highlights</i>	130
3.5.2	<i>Backlash</i>	130
3.5.3	<i>Dynamics</i>	131
3.6	Clutches and Brakes	132
3.6.1	<i>Clutch/Brake Types</i>	132
3.6.2	<i>Velocity Rating</i>	134
3.6.3	<i>Torque Rating</i>	134
3.6.4	<i>Duty Cycle/Temperature Limits</i>	135
3.6.5	<i>Timing</i>	137
3.6.6	<i>Control</i>	139
3.6.7	<i>Brake/System Timing</i>	140
3.6.8	<i>Soft Start/Stop</i>	140
3.7	Servo Couplings	140
3.7.1	<i>Inertia</i>	141
3.7.2	<i>Velocity</i>	141

3.7.3	<i>Torque</i>	141
3.7.4	<i>Compliance</i>	141
3.7.5	<i>Misalignment</i>	143
3.7.6	<i>Coupling Types</i>	143
3.8	Feedback Devices	146
3.8.1	<i>Optical Encoders</i>	146
3.8.2	<i>Magnetic Encoders</i>	152
3.8.3	<i>Capacitive Encoders</i>	153
3.8.4	<i>Magnetostrictive/Acoustic Encoders</i>	153
3.8.5	<i>Resolvers</i>	153
3.8.6	<i>Inductosyn</i>	157
3.8.7	<i>Potentiometer</i>	158
3.8.8	<i>Tachometers</i>	162
	References	164
	Additional Readings	165
4	System Design	167
4.1	Position, Velocity, Acceleration, Jerk, Resolution, Accuracy, Repeatability	167
4.1.1	<i>Position</i>	167
4.1.2	<i>Velocity</i>	169
4.1.3	<i>Acceleration</i>	170
4.1.4	<i>Jerk</i>	170
4.2	Three Basic Loops – Current/Voltage, Velocity, Position	170
4.2.1	<i>Current/Voltage Loop</i>	171
4.2.2	<i>Velocity Loop</i>	177
4.2.3	<i>Position Loop</i>	181
4.3	The Velocity Profile	182
4.3.1	<i>Preface</i>	182
4.3.2	<i>Incremental Motion</i>	183
4.3.3	<i>Constant Motion</i>	192
4.3.4	<i>Profile Simulation</i>	194
4.4	Feed Forward	195
4.5	Inertia	200
4.5.1	<i>Preface</i>	200
4.5.2	<i>Motor Selection</i>	202
4.5.3	<i>Reflected Inertia – Gearhead</i>	203
4.5.4	<i>Torque versus Optimum Ratio – Gearhead</i>	204
4.5.5	<i>Power versus Optimum Ratio – Gearhead</i>	204
4.5.6	<i>Optimal Conditions</i>	208
4.6	Shaft Compliance	210
4.6.1	<i>Basic Equations</i>	211
4.6.2	<i>System Components</i>	212
4.6.3	<i>Initial Simulation – Lumped Inertia</i>	212
4.6.4	<i>Second Simulation – Inclusion of Shaft Dynamics</i>	212

4.6.5	<i>Third Simulation – Compensation</i>	214
4.6.6	<i>Coupling Simulation</i>	215
4.7	Compensation	216
4.7.1	<i>Routh–Hurwitz</i>	216
4.7.2	<i>Nyquist</i>	217
4.7.3	<i>Bode</i>	217
4.7.4	<i>Root Locus</i>	218
4.7.5	<i>Phase Plane</i>	218
4.7.6	<i>PID</i>	218
4.7.7	<i>Notch Filter</i>	223
4.8	Nonlinear Effects	224
4.8.1	<i>Coulomb Friction</i>	224
4.8.2	<i>Stiction</i>	225
4.8.3	<i>Limit</i>	226
4.8.4	<i>Deadband</i>	226
4.8.5	<i>Backlash</i>	228
4.8.6	<i>Hysteresis</i>	229
4.9	The Eight Basic Building Blocks	230
4.9.1	<i>Rotary Motion – Direct Drive</i>	230
4.9.2	<i>Rotary Motion – Gearhead Drive</i>	234
4.9.3	<i>Rotary Motion – Belt and Pulley Drive</i>	237
4.9.4	<i>Linear Motion – Leadscrew/Ballscrew Drive</i>	239
4.9.5	<i>Linear Motion – Belt and Pulley Drive</i>	242
4.9.6	<i>Linear Motion – Rack and Pinion Drive</i>	245
4.9.7	<i>Linear Motion – Roll Feed Drive</i>	248
4.9.8	<i>Linear Motion – Linear Motor Drive</i>	251
	References	253
5	System Examples – Design and Simulation	255
5.1	Linear Motor Drive	255
5.2	Print Cylinder Control	257
5.3	Conveyor System – Clutch/Brake Control	261
5.3.1	<i>Determine Basic Parameters</i>	261
5.3.2	<i>Initial Component Selection</i>	264
5.3.3	<i>Simulate System</i>	264
5.4	Bang-Bang Servo (Slack Loop System)	267
5.5	Wafer Spinner	272
Appendix		275
A.1	Brushless Motor Speed/Torque Curves	275
A.1.1	<i>Thermal Resistance</i>	275
A.1.2	<i>Core Losses</i>	276
A.2	Inertia Calculation – Excel Program	277
A.3	Time Constants versus Viscous Damping Constant	277
A.4	Current Drive Review	279
A.5	Conversion Factors	285

A.6	Work and Power	286
A.6.1	<i>Work (Energy)</i>	286
A.6.2	<i>Power</i>	286
A.6.3	<i>Horsepower (HP)</i>	286
A.6.4	<i>Rotary Power</i>	287
A.7	I^2R Losses	287
A.7.1	<i>Conventional DC Motor</i>	287
A.7.2	<i>Three Phase Brushless DC Motor with Trapezoidal BEMF and Six Step Drive</i>	288
A.7.3	<i>Three Phase Brushless DC Motor with Sine Wave BEMF and Drive</i>	289
A.8	Copper Resistivity	290
Index		291