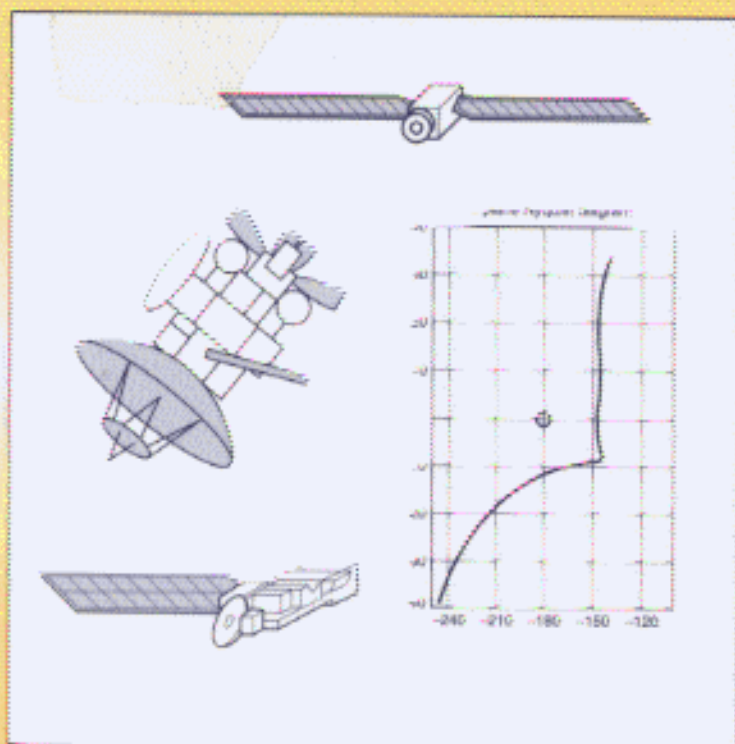


Control Engineering Series

CLASSICAL FEEDBACK CONTROL

With MATLAB



Boris J. Lurie
Paul J. Enright

CONTENTS

PREFACE	iii
TO INSTRUCTORS	xiii

Chapter 1

FEEDBACK AND SENSITIVITY	1
1.1 Feedback control system	1
1.2 Feedback: positive and negative	3
1.3 Large feedback	4
1.4 Loop gain and phase frequency responses.	6
1.4.1 Gain and phase responses	6
1.4.2 Nyquist diagram	9
1.4.3 Nichols chart	10
1.5 Disturbance rejection	11
1.6 Example of system analysis	12
1.7 Effect of feedback on the actuator nonlinearity	15
1.8 Sensitivity	17
1.9 Effect of finite plant parameter variations.	18
1.10 Automatic signal level control.	19
1.11 Lead and <i>PID</i> compensators	20
1.12 Conclusion and a look ahead	20
1.13 Problems	21

Chapter 2

FEEDFORWARD, MULTILoop, AND MIMO SYSTEMS	31
2.1 Command feedforward	31
2.2 Prefilter and the feedback path equivalent	33
2.3 Error feedforward	34
2.4 Black's feedforward method	35
2.5 Multiloop feedback systems	36
2.6 Local, common, and nested loops	37
2.7 Crossed loops and main/vernier loops	38
2.8 Manipulations of block diagrams and calculations of transfer functions.	40
2.9 MIMO feedback systems	43
2.10 Problems	46

Chapter 3

FREQUENCY RESPONSE METHODS.	52
3.1 Conversion of time-domain requirements to frequency domain	52
3.1.1 Approximate relations	52
3.1.2 Filters	56
3.2 Closed-loop transient response	58
3.3 Root locus	59

3.4	Nyquist stability criterion	61
3.5	Robustness and stability margins	63
3.6	Nyquist criterion for a system with an unstable plant	67
3.7	Successive loop closure stability criterion.	69
3.8	Nyquist diagrams for the loop transfer functions with poles at the origin	71
3.9	Bode integrals.	74
3.9.1	Minimum phase functions	74
3.9.2	Integral of feedback	75
3.9.3	Integral of resistance	76
3.9.4	Integral of the imaginary part.	78
3.9.5	Gain integral over finite bandwidth	78
3.9.6	Phase-gain relation	79
3.10	Phase calculations	81
3.11	From the Nyquist diagram to the Bode diagram	83
3.12	Non-minimum phase lag	85
3.13	Ladder networks and parallel connections of m.p. links.	86
3.14	Problems	88

Chapter 4

SHAPING THE LOOP FREQUENCY RESPONSE		94
4.1	Optimality of the compensator design	94
4.2	Feedback maximization	96
4.2.1	Structural design.	96
4.2.2	Bode step	97
4.2.3	Example of a system having a loop response with a Bode step.	100
4.2.4	Reshaping the feedback response	105
4.2.5	Bode cutoff	106
4.2.6	Band-pass systems	107
4.2.7	Nyquist-stable systems	108
4.3	Feedback bandwidth limitations	110
4.3.1	Feedback bandwidth	110
4.3.2	Sensor noise at the system output	111
4.3.3	Sensor noise at the actuator input	112
4.3.4	Non-minimum-phase shift	113
4.3.5	Plant tolerances.	114
4.3.6	Lightly damped flexible plants; collocated and non-collocated control.	116
4.3.7	Unstable plants	119
4.4	Coupling in MIMO systems.	120
4.5	Shaping parallel channel responses	121
4.6	Problems	125

Chapter 5

COMPENSATOR DESIGN.		130
5.1	Accuracy of the loop shaping	130
5.2	Asymptotic Bode diagram	131

5.3	Approximation of constant-slope gain response	133
5.4	Lead and lag links	135
5.5	Complex poles	137
5.6	Cascaded links	138
5.7	Parallel connection of links	141
5.8	Simulation of a PID controller	143
5.9	Analog and digital controllers	146
5.10	Digital compensator design	146
5.10.1	Discrete trapezoidal integrator	146
5.10.2	Laplace and Tustin transforms	148
5.10.3	Design sequence	151
5.10.4	Block diagrams, equations, and computer code	151
5.10.5	Compensator design example	153
5.10.6	Aliasing and noise	156
5.10.7	Transfer function for the fundamental	157
5.11	Command profiling	159
5.12	Problems	159

Chapter 6

ANALOG CONTROLLER IMPLEMENTATION		170
6.1	Active <i>RC</i> circuits	170
6.1.1	Operational amplifier	170
6.1.2	Integrator and differentiator	171
6.1.3	Noninverting configuration	172
6.1.4	Op-amp dynamic range, noise, and packaging	173
6.1.5	Transfer functions with multiple poles and zeros	174
6.1.6	Active <i>RC</i> filters	176
6.1.7	Nonlinear links	178
6.2	Design and iterations in the element value domain	180
6.2.1	Cauer and Foster <i>RC</i> two-poles	180
6.2.2	<i>RC</i> -impedance chart	182
6.3	Analog compensator, analog or digitally controlled	183
6.4	Switched-capacitor filters	184
6.4.1	Switched-capacitor circuits	184
6.4.2	Example of compensator design	185
6.5	Miscellaneous hardware issues	186
6.5.1	Ground	186
6.5.2	Signal transmission	187
6.5.3	Stability and testing issues	189
6.6	<i>PID</i> tunable controller	190
6.6.1	<i>PID</i> compensator	190
6.6.2	<i>TID</i> compensator	192
6.7	Tunable compensator with one variable parameter	193
6.7.1	Bilinear transfer function	193
6.7.2	Symmetrical regulator	194
6.7.3	Hardware implementation	196
6.8	Loop response measurements	196
6.9	Problems	200

Chapter 7

LINEAR LINKS AND SYSTEM SIMULATION	205
7.1 Mathematical analogies	205
7.1.1 Electro-mechanical analogies	205
7.1.2 Electrical analogy to heat transfer	208
7.1.3 Hydraulic systems	209
7.2 Junctions of unilateral links	211
7.2.1 Structural design	211
7.2.2 Junction variables	212
7.2.3 Loading diagram	213
7.3 Effect of the plant and actuator impedances on the plant transfer function uncertainty	214
7.4 Effect of feedback on the impedance (mobility)	215
7.4.1 Large feedback with velocity and force sensors	215
7.4.2 Blackman's formula	216
7.4.3 Parallel feedback	217
7.4.4 Series feedback	217
7.4.5 Compound feedback	218
7.5 Effect of load impedance on feedback	219
7.6 Flowchart for the chain connection of bidirectional two-ports	220
7.6.1 Chain connection of two-ports	220
7.6.2 DC motors	223
7.6.3 Motor output mobility	224
7.6.4 Piezoelements	224
7.6.5 Drivers, transformers, and gears	225
7.6.6 Coulomb friction	227
7.7 Examples of system modeling	227
7.8 Flexible structures	230
7.8.1 Impedance (mobility) of a lossless system	230
7.8.2 Lossless distributed structures	230
7.8.3 Collocated control	232
7.8.4 Non-collocated control	232
7.9 Sensor noise	233
7.9.1 Motion sensors	233
7.9.1.1 Position and angle sensors	233
7.9.1.2 Rate sensors	234
7.9.1.3 Accelerometers	235
7.9.1.4 Noise responses	235
7.9.2 Effect of feedback on the signal-to-noise ratio	236
7.10 Mathematical analogies to the feedback system	237
7.10.1 Feedback-to-parallel-channel analogy	237
7.10.2 Feedback-to-two-pole-connection analogy	237
7.11 Linear time-variable systems	238
7.12 Problems	240

Chapter 8

INTRODUCTION TO ALTERNATIVE METHODS OF CONTROLLER DESIGN.	245
8.1 QFT	245
8.2 Root locus and pole placement methods	247
8.3 State-space methods and full-state feedback.	249
8.4 LQR and LQG	253
8.5 H_∞ , μ -synthesis, and linear matrix inequalities.	255

Chapter 9

ADAPTIVE SYSTEMS	257
9.1 Benefits of adaptation to the plant parameter variations.	257
9.2 Static and dynamic adaptation.	259
9.3 Plant transfer function identification	259
9.4 Flexible and n.p. plants.	260
9.5 Disturbance and noise rejection	261
9.6 Pilot signals and dithering systems.	262
9.7 Adaptive filters	264

Chapter 10

PROVISION OF GLOBAL STABILITY	266
10.1 Nonlinearities of the actuator, feedback path, and plant.	266
10.2 Types of self-oscillation	267
10.3 Stability analysis of nonlinear systems	269
10.3.1 Local linearization	269
10.3.2 Global stability	270
10.4 Absolute stability	270
10.5 Popov criterion	271
10.5.1 Analogy to passive two-poles' connection	271
10.5.2 Different forms of the Popov criterion	274
10.6 Applications of Popov criterion	275
10.6.1 Low-pass system with maximum feedback	275
10.6.2 Band-pass system with maximum feedback	275
10.7 Absolutely stable systems with nonlinear dynamic compensation	276
10.7.1 Nonlinear dynamic compensator	276
10.7.2 Reduction to equivalent system	277
10.7.3 Design examples	278
10.8 Problems	286

Chapter 11

DESCRIBING FUNCTIONS	289
11.1 Harmonic balance	289
11.1.1 Harmonic balance analysis.	289
11.1.2 Harmonic balance accuracy.	290

11.2	Describing function	291
11.3	Describing functions for symmetrical piece-linear characteristics	292
11.3.1	Exact expressions	292
11.3.2	Approximate formulas	296
11.4	Hysteresis	297
11.5	Nonlinear links yielding phase advance for large-amplitude signals . . .	300
11.6	Two nonlinear links in the feedback loop	301
11.7	NDC with a single nonlinear nondynamic link	302
11.8	NDC with parallel channels	304
11.9	NDC made with local feedback	306
11.10	Negative hysteresis and Clegg Integrator	310
11.11	Nonlinear interaction between the local and the common feedback loops	311
11.12	NDC in multiloop systems	312
11.13	Harmonics and intermodulation	313
11.13.1	Harmonics	313
11.13.2	Intermodulation	314
11.14	Verification of global stability	315
11.15	Problems	317

Chapter 12

PROCESS INSTABILITY.	322
12.1 Process instability	322
12.2 Absolute stability of the output process	322
12.3 Jump-resonance	324
12.4 Subharmonics	327
12.4.1 Odd subharmonics	327
12.4.2 Second subharmonic	328
12.5 Nonlinear dynamic compensation	329
12.6 Problems	329

Chapter 13

MULTI-WINDOW CONTROLLERS.	331
13.1 Composite nonlinear controllers	331
13.2 Multi-window control	333
13.3 Switching between hot controllers and to a cold controller	335
13.4 Windup, and anti-windup controllers	336
13.5 Selection order	339
13.6 Acquisition and tracking	340
13.7 Time-optimal control	343
13.8 Examples	343
13.9 Problems	347

APPENDICES	349
Appendix 1 Feedback control, elementary treatment	349
A1.1 Introduction	349

A1.2	Feedback control, elementary treatment	349
A1.2.1	Feedback block diagram	349
A1.2.2	Feedback control	350
A1.2.3	Links	352
A1.3	Why control cannot be perfect	353
A1.3.1	Dynamic links	353
A1.3.2	Control accuracy limitations	354
A1.4	More about feedback	355
A1.4.1	Self-oscillation	355
A1.4.2	Loop frequency response	356
A1.4.3	Control system design using frequency responses	357
A1.4.4	Some algebra	357
A1.4.5	Disturbance rejection	358
A1.4.6	Conclusion	359
A1.5	New words	359
Appendix 2	Frequency responses	360
A2.1	Frequency responses	360
A2.2	Complex transfer function	362
A2.3	Laplace transform and the s -plane	362
A2.4	Laplace transfer function	363
A2.5	Poles and zeros of transfer functions	365
A2.6	Pole-zero cancellation, dominant poles and zeros	366
A2.7	Time-responses	367
A2.8	Problems	367
Appendix 3	Causal systems, passive systems, and positive real functions	371
Appendix 4	Derivation of Bode integrals	372
A4.1	Integral of the real part	372
A4.2	Integral of the imaginary part	372
A4.3	General relation	373
Appendix 5	Program for phase calculation	376
Appendix 6	Generic single-loop feedback system	379
Appendix 7	Effect of feedback on mobility	383
Appendix 8	Dependence of a function on a parameter	384
Appendix 9	Balanced bridge feedback	385
Appendix 10	Phase-gain relation for describing functions	386
Appendix 11	Discussions	387
A11.1	Compensator implementation	387
A11.2	Feedback: positive and negative	388
A11.3	Tracking systems	388
A11.4	Elements (links) of the feedback system	388
A11.5	Plant transfer function uncertainty	389
A11.6	The Nyquist stability criterion	390
A11.7	Actuator's output impedance	390
A11.8	Integral of feedback	391
A11.9	Bode integrals	391
A11.10	The Bode phase-gain relation	391
A11.11	What limits the feedback?	392

A11.12	Feedback maximization	392
A11.13	Feedback maximization in multi-loop systems.	394
A11.14	Nonminimum phase functions.	394
A11.15	Feedback control design procedure	394
A11.16	Global stability and absolute stability	395
A11.17	Describing function and nonlinear dynamic compensation	395
A11.18	Multi-loop systems	396
A11.19	MIMO systems	396
A11.20	The Bode's book	397
Appendix 12	Design sequence	398
Appendix 13	Examples.	399
A13.1	Industrial furnace temperature control.	399
A13.2	Scanning mirror of a mapping spectrometer.	400
A13.3	Rocket booster nutation control	402
A13.4	Telecommunication repeater with an NDC.	403
A13.5	Attitude control of a flexible plant	404
A13.6	Voltage regulator with a main, vernier, and local loops	405
A13.7	Telecommunication repeater.	407
A13.8	Distributed regulators	409
A13.9	Saturn V S-IC flight control system	410
A13.10	PLL computer clock with duty cycle adjustments	411
A13.11	Attitude control of solar panels	411
A13.12	Conceptual design of an antenna attitude control	412
A13.13	Pathlength control of an optical delay line	417
A13.14	MIMO motor control having loop responses with Bode steps	430
A13.15	Mechanical snake control.	431
Appendix 14	Bode Step toolbox.	432
BIBLIOGRAPHY		441
NOTATION		445
INDEX		449