

Frequency-Domain Control Design for High-Performance Systems

John O'Brien

The Institution of Engineering and Technology

Contents

1	Justification for feedback control	1
1.1	Tracking	2
1.1.1	Disturbance rejection	3
1.1.2	Sensitivity to parameter variation	3
1.1.3	Transient response	4
1.2	Exercises	5
2	Plant descriptions	7
2.1	Mathematical preliminaries	8
2.2	Plant modeling in the frequency domain	9
2.2.1	Laplace transform	9
2.2.2	Transfer function/transfer matrix	10
2.2.3	Frequency response	11
2.2.4	Nonminimum phase system	13
2.2.5	Bode phase/gain relationship	13
2.2.6	Nonminimum phase lag	14
2.3	Plant modeling in the time domain	16
2.3.1	Solution of the state differential equation	17
2.3.2	Controllability and observability	19
2.3.3	Minimal state space realizations	20
2.3.4	Diagonalizing the state matrix	20
2.3.5	Transfer function from the state equation	21
2.4	Linearization	22
2.5	System identification	24
2.6	Exercises	25
3	Feedback	27
3.1	Feedback	28
3.2	Sensitivity	29
3.3	Bode sensitivity integral	31
3.4	Bandwidth limitations	31
3.4.1	Sensor noise	31
3.4.2	Actuator limits	32
3.4.3	Plant limits – poles	32
3.4.4	Plant limits – zeros	34

3.4.5	Plant knowledge	37
3.4.6	Time delay	38
3.5	Exercises	38
4	Feedforward	41
4.1	Command feedforward	41
4.2	Prefilter	46
4.3	Exercises	48
5	Stability	49
5.1	Bounded-input, bounded-output stability	49
5.1.1	Marginally stable systems	50
5.1.2	BIBO stability of state equations	51
5.2	Zero input stability	52
5.2.1	Hidden modes	52
5.3	Nyquist Stability Criterion	54
5.4	Relative stability	63
5.5	Internal stability	67
5.6	Generalized Nyquist Stability Criterion	68
5.7	Gershgorin analysis	68
5.7.1	Case study: multiaxis control of a parallel robot	69
5.8	Lyapunov method	74
5.9	Direct method	77
5.10	Case study: set point control of a parallel robot	78
5.11	Kinematic set point control	78
5.11.1	Kinematic control law	80
5.11.2	Examples of kinematic set point control	80
5.11.3	Effect of mechanism singularities on the kinematic set point controller	82
5.12	Absolute stability	83
5.12.1	Circle Criterion	84
5.12.2	SISO case	85
5.12.3	Popov Criterion	86
5.13	Exercises	87
		91
6	Feedback design – linear	93
6.1	The Bode loop response	
6.1.1	Shaping the response below crossover: roll-off slope in between first and second order	93
6.1.2	Shaping the loop response above crossover: high-frequency slope and the Bode step	95
6.1.3	The complete loop shape	97
6.1.4	Case study: loop shaping	98
6.2	Phase stabilization	106
6.3	Nyquist-stable system	109

6.4	Two-input, single-output control	109
6.5	Single-input, two-output control	113
6.5.1	Case study: SITO control of a ship's rudder	115
6.5.2	Case study: poor application of Nyquist-stable control	120
6.6	Exercises	122
7	Feedback design – nonlinear	127
7.1	Anti-windup	127
7.2	Nonlinear dynamic compensation	128
7.2.1	Case study: nonlinear dynamic compensator design for a vibration suppression system	129
7.3	Multipurpose nonlinear dynamic compensation	143
7.3.1	Case study: anti-windup control	145
7.3.2	Case study: nonlinear dynamic compensation for multiple saturations	148
7.4	Variable gain for SITO feedback systems	155
7.4.1	Case study: HSS rate error variable gain SITO controller	156
7.5	Exercises	160
8	References	163
	Appendix: Proof of Bode sensitivity integral	165
	Bibliography	171
	Index	177