

Index

- Abel–Ruffini theorem, 63
- amplifier, 132
- analog computer, 133
- analytic function, 48, 57, 62, 221, 231, 260
 - Cauchy–Riemann conditions, 57
 - entire, 58
 - meromorphic, 218
- approximation, 4, 56, 141, 168, 203, 216
- argument principle, 218, 223, 226, 229
 - for negatively oriented contour, 220
- ballcock valve, 34
- bandwidth, 242, 258, 259
- BIBO, *see* bounded-input–bounded-output
- block-diagram, 1, 17
 - all stabilizing controllers, 283
 - closed-loop control, 8, 91, 255
 - closed-loop with input disturbance, 12, 31
 - closed-loop with input disturbance and measurement noise, 105, 138
 - closed-loop with reference, input disturbance, measurement noise, and feedback filter, 113
 - closed-loop with time-delay, 265
 - differential equation, 20
 - feedforward control, 278, 279
 - filter as feedback system, 282
 - filtering, 282
 - first-order differential equation, 127
 - integrator, 19
 - linear control of nonlinear systems, 153
 - open-loop control, 7
 - open-loop with input disturbance, 12
 - pendulum, 144
 - proportional control, 170
 - robust control, 262
 - robust tracking, 269
 - phase disturbance, 237
 - proportional–derivative control, 172
 - proportional–integral control, 99
 - proportional–integral–derivative control, 174
 - robust analysis, 262
 - second-order differential equation, 127
 - series connection, 91
 - system with input disturbance, 11
 - system with measured disturbance, 278
- Bode diagram, 185, 201, 216, 232, 236, 255
 - asymptotes, 201, 203, 206, 232
 - first-order model, 203
 - magnitude, 201, 202
 - phase, 201, 202
 - poles and zeros at the origin, 208
 - rational transfer-function, 202
 - second-order model, 205, 207
- Bode’s sensitivity integral, 258
- bounded signals, 69, 75, 93, 114, 137, 264
- capacitor, 52, 126, 132
 - as differentiator, 130
 - as integrator, 133
 - impulse, 131
 - losses, 131
- car steering, 148
 - equilibrium trajectory, 149
 - linearized model, 150
 - non-minimum-phase model, 216
 - nonlinear model, 149
- Cauchy’s residue theorem, 57, 59, 221, 260
- causality, 54, 62
 - Paley–Wiener, 62
- characteristic equation, 21, 175, 228
 - closed-loop, 176
 - first-order, 94, 98
 - rational function, 63
 - second-order, 98, 100
 - state-space, 136
 - transcendental, 226
- charge, 126
- circle criterion, *see* robustness
- closed-loop control, 8, 17
 - internal stability, 115
- communication channel, 282
- complementary sensitivity, 11, 92, 111
- continuous-time model, 17

- contour, 58, 62, 218
 - for assessing stability, 223
 - for stability analysis, 260
- indentation, 226, 231, 243
- inverse Laplace transform, 60
- orientation, 58, 62, 219, 220
- controllability, 139–141, 143, 262, 264
- convolution, 50, 53, 55, 56, 69
- cruise control
 - closed-loop frequency response, 101, 108
 - closed-loop sensitivity, 111
 - differential equation, 19
 - disturbance rejection
 - constant slope, 31
 - rolling hills, 109
 - impulse response, 56
 - integral control, 96, 98, 107, 169
 - root-locus, 179
 - internal stability, 116
 - nonlinear model, 28
 - proportional control, 24, 92, 98, 107
 - root-locus, 178
 - step response, 94
 - proportional–integral control, 99, 108, 116, 169, 171
 - nonlinear response, 102
 - pole–zero cancellation, 116
 - root-locus, 182
 - step response, 101
 - ramp response, 66, 73
 - steady-state, 67
 - saturation, 3
 - sensitivity, 11, 25
 - static model, 6
 - step response, 21, 64, 73
 - transfer-function, 56, 92
- curve fitting, 3, 6, 23
 - least-squares, 3, 4
- damper, 153
- damping, 35, 150, 167, 174, 189, 239, 270
 - overdamped, 167
 - ratio, *see* second-order model, 257
 - underdamped, 167, 191
- dB, *see* decibel
- DC gain, 106, 202
- DC motor, 104, 144
- dead-zone, 104
- decibel, 186, 201, 203
- derivative control, 165
- determinant, 136
- differential equations
 - homogeneous solution, 21
 - initial conditions, 21
 - linear, 22, 24, 56
 - nonlinear, 28, 126
 - ordinary, 17, 19, 22, 24, 29, 56
 - particular solution, 20
 - Runge–Kutta, 29
- differentiator, 130, 171
 - realization, 130
- digital, 6, 17
- discrete-time model, 17
 - aliasing, 18
 - sampling, 17, 127
- distribution, 51
- disturbance, 11, 17, 105, 151, 174, 261, 278
 - input, 30
 - measured, 278
 - rejection, 30, 35, 280, 281
 - asymptotic, 35
- dynamic model, 52
- eigenfunction, 75
- eigenvalue, 136, 142
- eigenvector, 136
- equilibrium, 142, 148, 150
 - closed-loop, 152
 - point, 141
 - trajectory, 142, 149
- error signal, 7, 9, 24, 189, 255
 - with measurement noise, 105
- estimation, 140
- estimator, 282
- examples
 - car steering, *see* car steering
 - cruise control, *see* cruise control
 - inverted pendulum, *see* pendulum in a cart
 - pendulum, *see* pendulum
 - pendulum in a cart, *see* pendulum in a cart
 - toilet water tank, *see* toilet water tank
- experiments, 1, 6, 18, 19, 22, 23, 28, 47, 56, 74, 154
- feedback, 5, 9, 20
 - controller, 7
 - in state-space, 138
- feedforward, 255, 278–280, 282
- filter, 113, 152, 279, 281
 - Kalman, 282, 283
- filtering, 255, 282
- first-order model
 - Bode diagram, 202
 - characteristic equation, 21
 - rise-time, 22
 - time-constant, 22
- Fourier series, 54
- Fourier transform, 47, 51, 54, 61, 62
- frequency domain, 47, 49, 92
- frequency response, 73, 74, 94, 201, 255
 - magnitude, 74
 - phase, 74

- gain, 8, 24, 26, 97
- harmonic oscillator, 167
- Hurwitz, 136, 137, 139, 142, 145, 153
- I controller, *see* integral control
- impulse response, 54, 69
- impulse signal, 51, 52, 77, 173
 - in capacitors, 131
 - sifting property, 77
- initial conditions
 - state, 135
- input saturation, 102, 153
- input signal, 1, 5, 17
- integral action, 33
- integral control, 110, 151
 - nonlinear model, 153
 - transfer-function, 96
 - wind-up, 103, 104
- integrator, 19, 95, 96, 110, 126, 153, 171, 189, 242, 269
 - gain, 97
 - in the controller, 35
 - in the system, 34, 35
 - initial conditions, 128
 - realization, 133
 - trapezoidal rule, 127
- inverted pendulum, *see* pendulum in a cart
- Kalman filter, *see* filter
- kinematic model, 150
- lag control, 210
- Laplace transform, 17, 25, 47, 51, 91
 - Bromwich integral, 61, 62
 - convergence, 48, 63, 70, 92
 - boundedness, 70
 - exponential growth, 47, 48
 - inverse, 49, 51, 57, 60, 71, 166
 - causality, 62
 - from residues, 60
 - rational function, 63
 - unicity, 61
 - table of pairs, 48
 - table of properties, 50
- Laurent series, 58, 62
- lead control, 185, 208
 - transfer-function, 185
- Lebesgue integral, 75
- linear model, 4, 47
- linearity, 50, 52, 128
- linearized model, 9, 126, 141, 150, 151
 - time-varying, 142
- loop transfer-function, 176, 185, 189, 227, 234, 236, 238, 243–245, 255, 258, 259, 265, 267, 274
- Lyapunov, 141, 145
 - linearized model stability, 141
 - Lyapunov function, 145, 264
- margin
 - gain, 235, 236, 243
 - phase, 235, 237, 243
 - stability, 238, 257
- mass, 18, 126, 142, 143, 146, 150, 279
- mass matrix, 147
- matrix exponential, 137
- maximum modulus principle, 260
- measurement, 7, 140, 184, 278
- measurement noise, 105, 111
- meromorphic, *see* analytic function
- MIMO, *see* multiple-input–multiple-output
- minimum-phase model, 214, 240
- model
 - dynamic, 17, 18
 - static, 17, 19
- modulator, 53
- moment of inertia, 126, 143, 144, 146, 150
- multiple-input–multiple-output, 135, 138, 140, 283
- neighborhood, 48, 57, 141
- Newton's laws, 18, 30, 140, 142, 143
- noise signal, 282
 - measurement, 256
- nominal model, 5, 6
- non-minimum-phase model, 205, 214, 258, 279
 - step response, 214
 - time-delay, 216
- nonlinear model, 4, 9, 28, 102, 141
 - integral control, 153
 - linear control, 150
- nonlinearity, 154, 262, 266, 270, 271, 274
- norms of signals and systems, 75
 - 1-norm, 76
 - 2-norm, 77, 262
 - H_2 norm, 77, 281, 283
 - H_∞ norm, 77, 238, 262, 265, 271, 281, 283
 - ∞ -norm, 76
 - p -norms, 75
- Nyquist diagram, 201, 229, 232, 235–238, 255, 265, 273, 274
- Nyquist stability criterion, 226–229, 236, 266, 277
- observability, 139–141, 143, 262, 264
 - Gramian, 137, 264
- open-loop control, 6
 - internal stability, 114
- optimization, 281, 282
- oscillations, 96, 99, 104, 108–110, 148, 166, 191, 257
- output signal, 1, 5, 17
- overshoot, 103, 104, 117, 167

- P controller, *see* proportional control
 Padé approximation, *see* time-delay
 Parseval's theorem, 77
 PD controller, *see* proportional–derivative control
 pendulum, 143, 183, 265
 block-diagram, 144
 Bode diagram, 239, 242
 data, 183
 direct design with root-locus, 191
 equilibrium, 144
 frequency-domain control, 238
 lead control, 185
 frequency response, 191
 root-locus, 185, 187
 with integral action, 189, 191
 linearized model, 145
 loop transfer-function, 240
 margins, 241, 245
 nonlinear model, 144
 simulation, 271
 Nyquist diagram, 240, 241, 243
 proportional control, 151, 169, 170
 proportional–derivative control, 172, 183
 root-locus, 183
 proportional–integral control, 184
 root-locus, 184
 robust control, 266
 circle criterion, 274
 robust tracking, 269
 sensitivity, 257
 transfer-function, 145
 pendulum in a cart, 146
 equilibrium, 147
 inverted, 147
 linearized model, 147
 nonlinear model, 146
 vector second-order model, 146
 physical realization, 5, 20, 112, 133
 PI controller, *see* proportional–integral control
 PID controller, *see* proportional–integral–derivative control
 piecewise
 continuous, 47, 49, 222
 smooth, 47, 51, 52, 222
 Plancherel's theorem, 77
 polar plot, 217, 223, 273, 277
 pole–zero cancellation, 56, 95, 97, 100, 106, 108, 111, 115, 178, 182, 187, 234, 279, 280
 in open-loop, 112
 in state-space, 139
 poles
 complex-conjugate, 68, 69, 115, 165
 definition, 58
 dominant, 171, 191
 multiplicity, 63, 66, 181
 rational function, 63
 unstable, 113
 positive-real, *see* transfer-function
 proportional control, 8
 transfer-function, 24
 proportional–derivative control, 172
 differential equation, 173
 proportional–integral control, 99, 110
 implementation with circuits, 133
 transfer-function, 99
 proportional–integral–derivative control, 165, 174, 189, 281
 transfer-function, 175
 pulse-width modulation, 105
 PWM, *see* pulse-width modulation
 ramp signal, 52, 66, 97
 rational function, 57, 63, 93
 partial fractions, 65, 67, 71, 221
 poles, *see* poles
 proper, 57, 65, 138, 175
 realization, 130
 strictly proper, 57, 63, 64, 138, 178, 180, 234
 zeros, *see* zeros
 realizability, 281, 282
 reference signal, 6, 17, 93, 255
 sinusoidal function, 94
 step function, 94
 regulation, 32, 107, 189
 regulator, 152, 153
 relative degree, 258, 259
 residue, 49, 57, 59, 62, 71, 166, 221
 rational function, 63
 resistor, 132
 rise-time, 22, 26, 98, 100, 101, 103
 robust control, 262, 266, 283
 robustness, 154, 170, 236–238, 243, 255, 258, 261, 265, 266, 279
 circle criterion, 267, 273
 small gain, 262, 271
 root-locus, 165, 175, 227, 234, 236, 237, 259
 asymptotes, 180, 185, 187, 190
 real roots, 179
 rules, 176, 177
 saturation, 103, 104, 154
 input, 26, 28, 153
 nonlinearity, 28
 second-order model, 165
 Bode diagram, 205
 characteristic equation, 165
 damping ratio, 165, 167, 206
 differential equation, 127
 discriminant, 99, 100
 natural frequency, 165, 206, 207
 damped, 167

- peak time, 167
- percentage overshoot, 168
- poles, 165
- realization, 129
- resonance frequency, 207
- rise-time, 168
- settling-time, 168
- simple pendulum, 143
- state-space realization, 134
- step response, 167
 - time-constant, 168
 - vector form, 146, 147
- sensitivity, 11, 97, 110, 238, 255, 278, 283
 - peaking, 258, 267
 - poles, 97
 - rational, 97
 - transfer-function, 93
 - zeros, 97, 106
- sensor, 24, 265
- simple pendulum, *see* pendulum
- simulation, 26, 102, 126, 133, 271
- single-input–single-output, 135, 138, 176, 208
- singularity, 57, 58, 62
 - isolated, 58
- sinusoidal signal, 73
 - amplitude, 73, 130
 - phase, 73
- SISO, *see* single-input–single-output
- small gain, *see* robustness
- stability, 69, 93, 112, 201, 218, 223
 - asymptotic, 69–71, 93, 114, 137, 141, 224
 - bounded-input–bounded-output, 69, 75, 264, 269
 - closed-loop, 229, 235
 - global, 264
 - internal, 114, 136, 139, 283
 - stabilizing controllers, 283
 - unstable, 74, 99, 148, 151
- state-space model, 126, 269
 - characteristic equation, 136
 - controllability, *see* controllability
 - differential equations, 134
 - feedback connection, 138
 - impulse response, 136
 - initial conditions, 135, 137
 - matrix exponential, 137
 - minimal realization, 139, 140, 262, 273
 - observability, *see* observability
 - poles, 136
 - realization, 282
 - state vector, 135, 141
 - strictly proper, 136
 - transfer-function, 135
 - steady-state response, 71–73
 - step response
 - experiment, 23
 - step signal, 50–52, 111, 281, 283
 - stepper motor, 104
 - summer, 128
 - superposition, 129, 166
 - system, 1
 - system identification, 24, 56
- Taylor series, 11, 57, 141
- time domain, 47, 49, 92
- time-constant, 19, 22, 26, 28, 98, 100, 101, 103
- time-delay, 216, 237, 265, 266
 - Padé approximation, 216
 - stability, 226
- time-invariant model, 47, 53, 91, 92, 150, 201, 223
- time-varying model, 53, 142, 150
 - impulse response, 55
 - stability, 142
- toilet water tank, 33, 126
 - differential equation, 33
 - disturbance rejection, 110
 - integrator, 33
 - proportional control, 34, 95
 - transfer-function, 95
- tracking, 6, 8, 93, 153, 184, 189, 255
 - asymptotic, 35, 94, 95, 97, 98, 100, 107, 256, 269, 280
 - asymptotic with input-disturbance rejection, 106–108
 - feedforward, 279
- tracking error, 25, 93, 105, 278
 - steady-state, 94
- transfer-function, 8, 47, 91
 - from differential equation, 55
 - from impulse response, 55
 - from input disturbance to output, 106
 - from reference to control, 100
 - from reference to error, *see* sensitivity
 - from reference to output, *see* complementary sensitivity
 - from state-space, 135
 - initial conditions, 55, 56
 - order, 57
 - poles, *see* poles
 - positive-real, 274
 - rational, *see* rational function
 - zero initial conditions, 56, 74
 - zeros, *see* zeros
- transient, 97
- transient response, 67, 71, 180
- triangle inequality, 76, 256, 264

uncertainty, 154, 262, 265, 271, 274, 279 structured, 271	waterbed effect, 258 Wright brothers, 9, 12
washout filter, 152 water heater, 1	zeros complex-conjugate, 115 rational function, 63