

# Index

- Ackermann's algorithm, 155
- actuator saturation, 203, 207, 208, 272
- additive uncertainty, 226
- AIC, 40, 42
- Akaike's information criterion, 37
- algebraic Riccati equation (ARE), 144, 149, 216, 217, 237
- analytical solution, 66–70, 128, 150, 262, 287
- anti-windup, 5, 208
- arc tangent Nyquist plot, 89, 90
- automatic tuning, 191, 192, 209
  - relay, *see* relay autotuning
  - Tsytkin's method, 218–220
- autonomous system, 67
  
- balanced realization, 33, 58, 59, 99–101, 281
  - Schur's, 100
- Bass–Gura algorithm, 155
- Bezout equation, 235, 236
- bilinear transform, 228, 229, 241
- block diagram, 1, 4, 24, 59, 96, 107, 110, 111, 116, 152, 186, 216, 217, 226, 230, 276, 278, 286
- Bode diagram, 7, 51, 84–88, 93, 100, 101, 134–138, 140, 141, 162, 163, 219, 220, 261, 263, 266, 268, 271, 283, 284, 288
  - magnitude, 235, 238, 248, 252, 255, 269
- bounded input–bounded output, 52
  
- canonical form, 56, 57, 59, 62
  - controllable, 30, 31
  - Jordanian, 31–33, 280
  - observable, 30
- Caputo's definition, 258, 259
  
- cascade PI controller, 205
- Cauchy's definition, 258
- Chien–Hrones–Reswick formula, 169, 182–184
- class, 260
- Cohen–Coon formula, 169, 184, 185
- complementary sensitivity function, 105, 222, 231
- complex plane, 180, 228
- connection
  - feedback, 23, 24, 261
  - parallel, 22, 34, 260
  - series, 13, 22, 24, 260
- constrained optimization, 125, 199, 200
- control strategy, 1, 3, 148, 149, 152, 170–172, 211, 212
- Control Systems Toolbox, 6–8, 23, 27, 28, 30, 34, 56–59, 72, 75, 78, 84, 85, 89, 95, 99, 133, 144, 153, 155, 158, 162, 216
- controllability, 51, 55–57, 59, 60, 157
  - Gramian, 51, 58, 59, 166
  - staircase form, 56, 57
- controllable canonical form, 30, 31
- controller
  - $\mathcal{H}_\infty$ , 215, 227, 237, 238, 241, 245, 290, 291
  - $\mathcal{H}_2$ , 246, 291
  - fractional-order, 257, 269
  - PD, 185, 194–196, 205, 269
  - PI, 118, 171, 173, 175, 176, 181–183, 185, 188, 189, 191, 204, 207, 269, 290
  - PID, 169–214
- coprime factorization, 235–237
- crossover frequency, 135, 137, 139, 140, 142, 143, 173, 176, 178, 191, 209, 210,

- 222, 266, 288  
CtrlLAB, 5–7, 9, 275
- damping ratio  
  iso-, 78, 81
- DC (direct-current) gain, 42, 178, 179
- decoupling, 5, 133, 159–162, 244  
  dynamic, 160, 162  
  with state feedback, 159–162
- default discretization, 35
- delayed system, 79, 114
- describing function, 120, 209, 210
- descriptor system, 228
- difference equation, 44, 45
- differential equation, 14, 16, 19, 257  
  fractional-order, 257, 261, 262
- differential Riccati equation, 144, 148
- differentiation, 16, 258  
  fractional-order, 258, 259, 263
- direct-current (DC) gain, 42, 178, 179
- discrete-time Riccati equation, 147
- discretization, 35
- disturbance, 53, 184, 188, 189, 215, 220, 226  
  rejection, 182, 183, 189–191
- dominant poles, 81
- dual, 30, 57, 157
- dynamic decoupling, 160, 162
- feedback connection, 23, 24, 261
- filter  
  Kalman, 216–218, 220–222, 224, 246  
  low-pass, 231, 266  
  Oustaloup's, 263, 264, 267, 268  
  refined Oustaloup's, 264–268
- first-order lag and integrator plus dead time (FOIPDT), 195, 196, 205
- first-order plus dead time (FOPDT), 169, 173, 175, 179, 184, 193, 290
- fixed step, 112
- FOIPDT (first-order lag and integrator plus dead time), 195, 196, 205
- FOPDT (first-order plus dead time), 169, 173, 175, 179, 184, 193, 290
- Fourier series expansion, 42, 211
- fractional transformation representation, 227, 231
- fractional-order, 257–274  
  calculus, 258, 259  
  controller, 257, 269  
  differential equation, 257, 261, 262  
  differentiation, 258, 259, 263  
  Caputo's definition, 258, 259  
  Cauchy's definition, 258  
  Grünwald–Letnikov definition, 258, 259, 262, 263  
  Riemann–Liouville definition, 258, 259  
  transfer function, 260, 261, 267, 268
- frequency responses, 5, 43, 64, 65, 83–91, 173, 178–180, 283
- gain margin, 88, 89, 135, 137, 176, 222
- general mixed sensitivity problem, 231
- Genetic Algorithm Optimization Toolbox (GAOT), 9, 206
- genetic algorithm (GA), 206
- GA (genetic algorithm), 206
- GAOT (Genetic Algorithm Optimization Toolbox), 9, 206
- Grünwald–Letnikov definition, 258, 259, 262, 263
- $\mathcal{H}$ -norm, 65
- $\mathcal{H}_2$ -norm, 65, 66, 97, 215, 227
- $\mathcal{H}_\infty$ -norm, 215, 227, 235, 237
- $\mathcal{H}_2$  controller, 246, 291
- $\mathcal{H}_\infty$  controller, 215, 227, 237, 238, 241, 245, 290, 291  
  optimal, 242, 244, 248, 250, 254, 271, 291  
  standard, 227
- Hankel matrix, 155
- Hankel norm, 100, 101
- Hardy space, 3, 5, 65
- identification  
  system, 4, 13, 36–45, 133, 180
- impulse response, 51, 62, 63, 70, 75, 76, 119, 228, 283, 284
- impulse signal, 65, 76, 97, 119, 286, 287

- integral of absolute error (IAE), 97, 161, 187, 201, 205, 206, 251, 252, 270
- integral of squared error (ISE), 97, 98, 188–191, 195
- integrator plus dead time (IPDT), 169, 194
- internal stability, 51–55
- internal structure, 4, 19, 36, 57, 208
- inverse system, 83
- inverse Z transform, 69
- IPDT (integrator plus dead time), 169, 194
- ISE (integral of squared error) criterion, 97, 98, 188–191, 195
- iso-damping, 78, 81
- iso-frequency, 78
- ITAE (integral of absolute error) criterion, 97, 161, 187, 201, 205, 206, 251, 252, 270
- Jordanian canonical form, 31–33, 280
- Kalman decomposition, 51, 59–61
- Kalman filter, 216–218, 220–222, 224, 246
- $\mathcal{L}$ -norm, 65
- $\mathcal{L}_1$ -norm, 65
- $\mathcal{L}_2$ -norm, 65
- $\mathcal{L}_\infty$ -norm, 65
- $\mathcal{L}_p$ -norm, 64
- Laplace transform, 4, 13–16, 26, 62, 64, 68, 69, 72, 76, 77, 97, 171, 259–261  
inverse, 15, 68
- lead-lag compensator, 133–143, 201, 275, 288
- Lebesgue space, 65
- limit cycle, 107, 120, 123, 124, 210, 211
- linear quadratic Gaussian control (LQG), 3, 215–225
- linear quadratic regulator (LQR), 3, 143, 144, 147, 166, 199
- linear system  
fractional-order,  
state space, 3, 4, 7, 13, 19–21, 26–35, 51, 55–57, 59, 62, 64, 67, 72, 73, 99–101, 108, 125, 126, 143, 144, 154–157, 159, 160, 216, 218, 221, 227–229, 231, 232, 254, 277–279  
transfer function, 4, 7, 13, 16–19, 21, 22, 24, 25, 27, 29, 34, 39, 45, 54, 57–59, 62, 63, 65, 68, 73, 83, 87, 91, 93, 95, 108, 136, 139, 178, 186, 191, 220, 222, 223, 227, 228, 232, 233, 236, 260, 265, 269, 277–279
- linear time invariant (LTI), 16, 20, 124–126, 130, 143
- logarithmic Nyquist plot, *see* Nyquist plot,  
logarithmic
- loop transfer recovery (LTR), 3, 215, 221, 223, 225
- low-pass filter, 171, 231, 266
- LQG (linear quadratic Gaussian control), 3, 215–225
- LQR (linear quadratic regulator), 3, 143, 144, 147, 166, 199
- LTI (linear time invariant), 16, 20, 124–126, 130, 143
- LTR(loop transfer recovery), 3, 215, 221, 223, 225
- Lyapunov equation, 10, 58
- Maclaurin series, 62, 95, 96
- magnitude Bode diagram, 235, 238, 248, 252, 255, 269
- Markov parameters, 51, 63, 64
- MATLAB toolbox  
CtrlLAB, 5–7, 9, 275  
Genetic Algorithm Optimization Toolbox (GAOT), 9, 206  
Optimal Controller Designer (OCD), 199, 203–207, 272  
PID\_Tuner, 197–199  
Robust Control, 9, 100, 101, 215, 218, 223, 227–229, 232, 238, 243, 246, 252  
Simulink, 4–6, 107–267, 272, 275, 278, 280  
Symbolic, 9, 15, 16, 68, 70
- measurement noise, 53, 218

- minimum
  - phase, 153, 233–235, 237
  - realization, 22, 34, 35, 45, 61, 62
  - sensitivity problem, 233, 234
- Mittag–Leffler function, 262
- mixed stability, 238
- model conversion, 4, 13, 26, 27, 39, 43, 45, 67
- model mismatch, 215
- model reduction, 4, 51, 58, 59, 91–101, 180, 245, 263, 281–283
  - optimal Hankel norm approximation, 100, 101, 281
  - Padé approximation, 91, 93–97, 115, 126, 268, 281
  - Routh approximation, 94, 95, 281
  - Schur’s balanced realization, 100
  - suboptimal reduction, 177, 198, 267, 268, 281
- multi-input–multi-output, 7, 18
- multiplicative uncertainty, 226
- multivariable system, 18, 35, 44, 45, 75, 77, 107, 113, 115, 126, 146, 159–162, 228, 243–245
- natural frequency, 162, 167, 255, 291
- Nichols chart, 84, 85, 142, 143, 240–243, 246–248, 250, 251, 254, 261, 264, 283, 284, 291
- nominal value, 238, 271
- nonminimum phase model, 224, 235–242
- nonlinear system, 5, 19, 107, 110, 120, 123–127, 129, 280, 286, 287
- nonlinearity, 107, 108, 121–123, 209, 210, 278
  - double-valued, 107, 120–122
  - piecewise linear, 107, 120
  - relay, 121, 209–211
  - saturation, 109, 118, 207
  - single-valued, 107, 120–122
  - static, 120, 122, 210
- Nyquist plot, 42, 51, 84, 85, 87–91, 134, 136, 173, 176, 178, 210, 221, 223, 225, 261, 264, 283, 284
  - atan, 89, 90
  - logarithmic, 90, 91
- Nyquist Theorem, 87
- observability, 51, 57–60
  - Gramian, 58, 59
  - staircase form, 57, 58
- observable canonical form, 30
- observer, 3, 133, 149–154, 157, 216, 237
- observer-based
  - controller, 133, 288
  - regulator, 154, 158
- OCD (Optimal Controller Designer), 199, 203–207, 272
- operating point, 124, 125
- Optimal Controller Designer (OCD), 199, 203–207, 272
- optimal control, 169, 199, 201–207
- optimal Hankel norm approximation, 100, 101, 281
- optimization, 97, 98, 169, 199–203, 205, 206, 218
  - constrained, 125, 199, 200
  - Genetic Algorithm Toolbox, 9, 206
  - unconstrained, 199, 200
- optimum PID controller, 169, 193, 194, 290
- ordinary differential equation (ODE), 14, 16, 19, 257
- Oustaloup recursive approximation, 263, 264, 267, 268
  - refined, 264–268
- overshoot, 71, 72, 74, 78, 103, 135, 140, 163, 170, 171, 181–183, 185, 186, 194, 202, 239
- Padé approximation, 91, 93–97, 115, 126, 268, 281
- parallel connection, 22, 34, 260
- PD controller, 185, 194–196, 205, 269
- phase margin, 88, 89, 135, 136, 139–143, 163, 219–222, 254, 287, 288
  - assignment, 191
- PI controller, 118, 171, 173, 175, 176, 181–183, 185, 188, 189, 191, 204, 207, 269, 290
- $PI^{\lambda}D^{\mu}$  controller, 269

- PID controller, 169–214
  - anti-windup, 5, 208
  - Chien–Hrones–Reswick, 169, 182–184
  - Cohen–Coon, 169, 184, 185
  - for FOIPDT plant, 195, 196, 205
  - for IPDT plant, 169, 194
  - fractional-order, 269
  - modified Ziegler–Nichols, 169, 187
  - optimum setting, 169, 193, 194, 290
  - phase margin assignment, 191
  - refined Ziegler–Nichols, 169, 185–187, 289
  - Wang–Juang–Chan, 169, 187, 188, 270
  - Ziegler–Nichols, 169, 173–187, 193, 194, 289
- PID\_Tuner, 197–199
- plant augmentation, 225, 227, 232
- plant model, 53, 82, 93, 100, 101, 117, 133, 135, 136, 139, 140, 148, 149, 155, 156, 162, 169, 170, 173, 176, 181, 183, 187, 188, 191, 193–197, 201, 205, 207, 210–212, 215, 218, 224, 226, 228, 231–234, 238, 239, 241, 246, 257, 271, 272, 279, 280, 288–290
  - FOIPDT, 195, 196, 205
  - FOPDT, 169, 173, 175, 179, 184, 193, 290
  - IPDT, 169, 194
  - minimum phase, 153, 233–235, 237
  - nonminimum phase, 224, 235–242
  - unstable FOPDT, 196
- pole placement, 133, 154–159, 161, 236
  - Ackermann’s algorithm, 155
  - Bass–Gura’s algorithm, 155
  - robust algorithm, 155–157
- prefilter, 2
- pseudorandom binary sequence (PRBS), 42–45
- ramp response, 76
- realization, 58, 59, 61, 62, 99, 100, 153, 275, 280
  - balanced, 33, 101, 281
  - minimum, 22, 34, 35, 45
- reduced order model, 59, 91, 93, 94, 96–101, 177, 193, 268, 270, 281, 283
- refined Oustaloup recursive approximation, 264–268
- refined Ziegler–Nichols tuning, 169, 185–187, 289
- relay, 121, 209–211
  - autotuning, 5, 191, 209
- Riccati equation, 146, 147, 216, 220, 237
  - algebraic, 144, 149, 216, 217, 237
  - differential, 144, 148
  - discrete-time, 147
- Riemann–Liouville definition, 258, 259
- rise time, 72
- Robust Control Toolbox, 9, 100, 101, 215, 218, 223, 227–229, 232, 238, 243, 246, 252
- robust pole placement algorithm, 155–157
- root locus, 3, 51, 77–83, 162, 163, 170, 283, 284
- Routh approximation, 94, 95, 281
- sampling interval, 17, 18, 21, 35, 38, 40, 44, 53, 69, 74, 79, 86, 87, 116, 117, 157
- saturation, 109, 118, 207
  - actuator, 203, 207, 208, 272
- Schur decomposition, 295
- Schur’s balanced realization, 100
- sensitivity function, 64, 222, 231, 233, 235, 248, 251
- sensitivity problem, 231, 233, 240, 291
  - general mixed, 238
  - minimum, 233, 234
- series connection, 13, 22, 24, 260
- settling time, 72, 74
- similarity transformation, 30, 59–62
- Simulink, 4–6, 107–267, 272, 275, 278, 280
- single input–single output, 7, 18
- SISOTool, 162, 163
- small gain theorem, 225, 226
- stability, 3, 51–55, 83, 86–90, 94, 95, 287
  - assessment, 51–53
  - internal, 51–55

- stability margins, 3, 220
- stabilizing controller, 227, 233, 234, 236, 245
- standard transfer function, 13, 161, 162, 251, 252
- state augmentation, 67, 68, 231
- state feedback, 144, 146, 147, 153–157, 159, 160, 162, 216, 218, 221, 246, 254
  - decoupling with, 159, 161
- state space, 3, 4, 7, 13, 19–21, 26–35, 51, 55–57, 59, 62, 64, 67, 72, 73, 99–101, 108, 125, 126, 143, 144, 154–157, 159, 160, 216, 218, 221, 227–229, 231, 232, 254, 277–279
- steady-state, 42
  - error, 171, 176, 194, 195, 288
  - response, 62, 64, 213
  - value, 71, 72, 144, 178, 241
- step response, 70, 73–75, 115, 135, 137, 138, 141, 143, 145, 148, 149, 151, 152, 163, 170–172, 176, 179, 181, 182, 184, 185, 191, 196, 199, 220, 235, 240, 243, 246, 251, 253, 254, 262, 268, 270–272, 287, 290
- suboptimal reduction, 177, 198, 267, 268, 281
- Symbolic Toolbox, 9, 15, 16, 68, 70
- System Identification Toolbox, 4, 9, 13, 36–45, 133, 180
- Taylor series expansion, 62–64, 91, 265
- time domain response, 77, 87, 261, 262
  - impulse response, 51, 62, 63, 70, 75, 76, 119, 228, 283, 284
  - ramp response, 76
  - step response, 70, 73–75, 115, 135, 137, 138, 141, 143, 145, 148, 149, 151, 152, 163, 170–172, 176, 179, 181, 182, 184, 185, 191, 196, 199, 220, 235, 240, 243, 246, 251, 253, 254, 262, 268, 270–272, 287, 290
- time moment, 62, 63, 95
- time varying system, 107, 113, 118, 119, 144
- transfer function, 4, 7, 13, 16–19, 21, 22, 24, 25, 27, 29, 34, 39, 45, 54, 57–59, 62, 63, 65, 68, 73, 83, 87, 91, 93, 95, 108, 136, 139, 178, 186, 191, 220, 222, 223, 227, 228, 232, 233, 236, 260, 265, 269, 277–279
  - discrete-time, 18, 36, 40, 43, 69, 79, 127
  - fractional-order, 260, 261, 267, 268
  - matrix, 18, 26, 27, 29, 39, 44, 45, 114, 160
  - standard, 13, 161, 162, 251, 252
- transmission zero, 28, 222
- tree variable, 227–229, 231, 232, 238, 243
- Tsympkin's method, 209–211
- Tustin transform, 229
  - bilinear, 228, 229, 241
- two degrees-of-freedom control, 2
- two-port state-space, 227, 230, 232, 237, 238, 243, 244, 246
- uncertainty, 64, 149, 215, 225, 226, 238, 243
  - additive, 226
  - multiplicative, 226
  - unstructured uncertainty, 226, 227
- unconstrained optimization, 199, 200
- undershoot, 241
- unity negative feedback, 53, 77, 87, 153, 261
- unstable FOPDT (first-order plus dead time), 196
- variable step, 112
- Wang–Juang–Chan formula, 169, 187, 188, 270
- weighting function, 97, 215, 221, 230–235, 238, 240–243, 247–254, 271, 291
- weighting matrix, 143, 144, 146–149, 153, 166, 199, 216, 221, 222
- well-posedness, 53, 54, 226
- Youla parameterization, 233
- Z transform, 18
  - inverse, 69
- zero initial conditions, 15, 16, 26, 103

- zero-order-hold (ZOH), 35, 116, 117
- zero-pole-gain model, 4, 13, 21, 27, 28, 34, 51, 94, 108, 277, 278, 280
- Ziegler–Nichols formula, 169, 173–187, 193, 194, 289
- modified algorithm, 169, 187
- refined tuning, 169, 185–187, 289
- ZOH (zero-order-hold), 35, 116, 117