

INDEX

A

Adaptive control, MPC, 191–194
 Algorithms, MPC
 control algorithm, 135
 description, 136
 GPC, 145
 robust stability constraints, 182–184
 stability constraints, 181–182
 Asymptotic stability, MPC, 146

B

Behavior
 f behavior, 18–22
 hysteresis, 25–26
 MPC system, 134, 156–157
 BIBO stability, *see* Bounded-input–
 bounded-output stability
 Bounded dispersions
 bubble columns, 91–100
 fluidized beds, 91, 99
 mathematical model, 73–90
 model parameter estimation, 90–91
 Bounded-input–bounded-output stability,
 149–150
 Bubble columns
 bounded dispersions, 91–92
 bubble rise velocity effect, 94
 column diameter effect, 96
 dispersion coefficient, 45–46
 dispersion effect, 95
 dispersion height effect, 96–98
 f behavior, 21–22
 gas density effect, 94
 gas phase, 2–3
 heterogeneous regime, 3
 hold-up parameter effect, 95
 mathematical model, 73–90
 model *vs.* experimental values, 99–100
 Sparger resistance effect, 92–94
 terminal rise velocity, 42–44
 unbounded bed analysis, 68–69

virtual mass coefficient, 46
 Buoyancy
 in fluidized bed, 116–117
 in multiphase systems, 22–23
 from pressure gradients, 121–122
 Business concepts, in multiscale MPC,
 195–196

C

Chance constraint, MPC, 197
 Closed-loop stability
 for MPC nonminimum-phase process,
 157–159
 for MPC performance, 185–186
 sensitivity, 167–169
 Coefficients
 dispersion coefficient, 22, 41, 45–46, 53–
 58, 63
 virtual mass coefficient, 22, 41–42, 46, 58,
 61–63
 Constraints, MPC
 chance constraint, 197
 end constraints, 178, 197
 inequality constraints, 142–145
 input constraints, 178, 183
 input move constraints, 177, 183
 output constraints, 178
 robust stability constraints, 182–184
 softenend state constraints, 183
 stability, 181–182
 system constraints, 169–170
 Continuous feedback, for MPC nonlinear
 process, 162–163
 Continuous stirred tank reactor, 148–149
 Contraction
 solid–liquid fluidized bed, 110
 three-phase fluidized beds, 105–109,
 111–113
 Control algorithm, in MPC conception, 135
 Control theory, classical, and MPC,
 135–136
 CSTR, *see* Continuous stirred tank reactor

D

Dimensionality, in multiscale MPC, 195
 Dispersed phase, solid–liquid fluidized beds, 3
 Dispersion coefficient
 bubble columns, 45–46
 in fluidized beds, 41, 53–58
 in gas–liquid bubble columns, 63
 in multiphase systems, 22
 Dispersions
 bounded, 73–100
 unbounded, 6–22
 Disturbance, MPC prediction, 177
 DMC, *see* Dynamic matrix control
 Drag force, in multiphase systems, 23
 Dynamic matrix control, MPC systems, 159
 Dynamic programming, MPC, 196–197

E

Elasticity, fluidized beds, 26, 28–29
 Elastic wave velocity equations, 30–32
 End constraints, MPC, 178, 197
 Energy dissipation, in fluidized bed, 117–121
 Engineering concepts, in multiscale MPC, 195–196
 Equations
 bubble column mathematical model, 73–75
 elastic wave velocity, 30–32
 linear stability continuity, 82–84
 linear stability momentum, 84–88
 solid–liquid fluidized beds, 7–12
 Expansion
 solid–liquid fluidized bed, 110
 three-phase fluidized beds, 105–109, 111–113

F

f behavior
 bubble columns, 21–22
 fluidized beds, 18–20
 Feedback, continuous, MPC, 162–163
 FG stability, *see* Finite-gain stability
 Finite-gain stability, 150–152, 155

Finite-impulse-response model, 138–139, 177–181
 Finite prediction horizon, 163–164
 FIR, *see* Finite-impulse-response model
 Fluid density, in fluidized beds, 48–49
 Fluidized beds
 bounded analysis, 100–103
 bounded dispersions, 91
 dispersion coefficient, 41
 elasticity, 26
 elastic wave velocity, 30–32
 f behavior, 18–20
 force balance equations, 27
 gas–solid, *see* Gas–solid fluidized beds
 model vs. experimental values, 99
 nomenclature, 122–127
 particle forces, 116–122
 slip velocity, 41
 solid–liquid, *see* Solid–liquid fluidized beds
 stability vs. instability, 26–27
 three-phase, 103–113
 transition, 28–29
 unbounded analysis, 65, 68–69, 100–103
 virtual mass coefficient, 41–42
 voidage propagation velocity, 29–30
 Fluid viscosity, in fluidized beds, 47–48
 Force, particle in fluidized bed
 buoyancy, 116–117
 energy dissipation, 117–121
 pressure gradients, 121–122
 Fragility, MPC systems, 165–169, 184–185

G

Gas bubbles
 diameter, 61
 rise velocity, 94
 solids-free liquid wake, 110–111
 wake volume, 108
 Gas density, in bubble columns, 94
 Gas–liquid bubble columns
 bubble diameter effect, 61
 dispersion coefficient effect, 63
 hysteresis behavior, 26
 Richardson–Zaki index effect, 63–65
 slip velocity, 44–45
 stability analysis, 36–40
 stability maps, 61

terminal rise velocity effect, 61
 unbounded dispersions, 18
 virtual mass coefficient effect, 61–63
 Gas phase, in bubble columns, 2–3
 Gas–solid fluidized beds
 dispersion coefficient effect, 53–58
 fluid density effect, 48–49
 fluid viscosity effect, 47–48
 particle density effect, 49–53
 particle diameter effect, 53
 particle phase, 3
 stability analysis, 24–26, 32–36
 stability maps, 46–47
 unbounded dispersions, 15–18
 virtual mass coefficient effect, 58
 Generalized predictive control, for unconstrained MPC algorithm, 145
 Global asymptotic stability, MPC, 147
 GPC, *see* Generalized predictive control

H

Heavy oil fractionator, stability, 165
 Heterogeneous regime, bubble columns, 3
 Heuristic models, three-phase fluidization, 105–109
 Hold-up pressure correlation model, 115–116
 Hydrodynamic models, for fluidized bed stability, 26
 Hysteresis behavior
 gas–liquid bubble columns, 26
 gas–solid fluidized beds, 25–26

I

Inequality constraints, absence in MPC, 142–145
 Input constraints, MPC, 178, 183
 Input move constraints, MPC, 177, 183
 Input-output models, MPC, 189
 Integrators, MPC systems, 159–161

K

Kinematic wave velocity, stability, 27

L

Linearization, solid–liquid fluidized beds, 12–15
 Linear models, MPC, 170–172, 189
 Linear–quadratic regulator, and MPC, 136–137
 Linear stability analysis, bubble column
 batch operation, 88
 boundary condition linearization, 81–82
 continuity equations, 82–84
 momentum equations, 84–88
 Y direction averaging, 78–81
 Liquid–liquid spray columns, unbounded dispersions, 18
 Liquids, terminal bubble velocity, 43–44
 LQR, *see* Linear–quadratic regulator

M

Mathematical model, bubble columns
 boundary conditions, 75–77
 cylindrical columns, 89–90
 equations, 73–75
 linear stability analysis, 77–88
 MIMO, *see* Multi-input–multi-output system
 Model parameters
 bounded dispersions, 90–91
 bubble columns, 42–46
 fluidized beds, 41–42
 Model predictive control
 algorithms, 135–136, 145, 181–184
 in classical control theory, 135–136
 conceptual unification, 187–188
 constraints, 169–170, 197
 dynamic programming, 196–197
 enhancements, 198
 fragility, 165–169, 184–185
 industrial origins, 134–135
 integrators, 159–161
 linear model, 170–172
 and LQR, 136–137
 model uncertainty, 165
 multiscale MPC, 194–196
 nonlinearity, 162–164
 nonlinear process model, 140, 172–174
 nonminimum phase, 157–159
 on-line optimization, 156–157

- performance, 185–186
 - process models, 188–194
 - as real-time problem, 133–134
 - robust performance, 185–186
 - robust stability, 176–184
 - short horizons, 157–159
 - stability proof, 174–176
 - stability regions, 160–161
 - stochastic disturbance model, 140
 - stochastic objective function, 140–142
 - system behavior, 134
 - theory development, 198–199
 - traditional formulation, 137–139
 - unstable process model, 140
 - unstable units, 159–161
 - without inequality constraints, 142–145
 - Models
 - bubble columns, 73–90
 - FIR, 138–139, 177–181
 - for fluidized bed stability, 26
 - hold-up pressure correlation, 115–116
 - MPC
 - input-output, 189
 - linear model, 170–172, 189
 - nonlinear process, 140, 172–174, 189
 - process, 188–194
 - state-space, 189–191
 - stochastic disturbance, 140
 - unstable process, 140
 - pressure–hold-up correlation, 115–116
 - three-phase fluidization, 105–109
 - Moving horizon-based state estimation, MPC models, 189–191
 - MPC, *see* Model predictive control
 - Multi-input–multi-output system, for MPC, 177–181
 - Multiphase systems
 - bounded vs. unbounded analysis, 100–103
 - buoyancy force, 22–23
 - dispersion coefficient, 22
 - drag force, 23
 - pressure, 22
 - regime transition, 23–24
 - virtual mass coefficient, 22
- N**
- Nonlinear process
 - MPC models, 140, 172–174, 189
 - MPC systems, 162–164
 - Nonminimum phase, MPC, 157–159
- O**
- On-line optimization, MPC, 156–157, 177–181, 186, 191–194
 - Optimization paradigms, in multiscale MPC, 196
 - Output constraints, softened, MPC, 178
- P**
- Particles, in fluidized beds
 - buoyancy, 116–117
 - density, 49–53
 - diameter, 53
 - energy dissipation, 117–121
 - phase, 3
 - pressure gradients, 121–122
 - Performance, MPC, 185–186
 - Phase transition, in fluidized beds, 28–29
 - p -norms, 149
 - Point of transition, solid–liquid fluidized bed, 110
 - Pressure
 - gradients in fluidized bed, 121–122
 - hold-up correlation model, 115–116
 - in multiphase systems, 22
 - Process models, MPC, 140, 172–174, 188–194
 - Process state
 - MPC output prediction, 177
 - MPC prediction, 183
 - MPC SISO, 137–138
- R**
- Real-time problem, MPC, 133–134
 - Regime transition, theoretical analysis, 23–24
 - Reynolds averaging, for solid–liquid fluidized beds, 8–9
 - Richardson–Zaki index, in gas–liquid bubble columns, 63–65
 - Robust stability, MPC constraint prediction, 183–184

S

- Short horizons, MPC, 157–159
- Single-input–single-output process, in MPC, 137–138
- SISO, *see* Single-input–single-output process
- Slip velocity
 - fluidized beds, 41
 - gas–liquid bubble columns, 44–45
- Softened state constraints, MPC, 183
- Software, for multiscale MPC, 196
- Solid–liquid fluidized beds
 - contraction–expansion prediction, 111–112
 - dispersion coefficient effect, 53–58
 - equations, 7–12
 - expansion and contraction, 110
 - fluid density effect, 48–49
 - fluid viscosity effect, 47–48
 - heterogeneous–heterogeneous stability, 112–113
 - homogeneous–heterogeneous stability, 112
 - homogeneous–homogeneous stability, 113
 - linearization, 12–15
 - particle density effect, 49–53
 - particle diameter effect, 53
 - particle phase, 3
 - stability analysis, 32–36
 - stability maps, 46–47
 - steady-state conditions, 12
 - virtual mass coefficient effect, 58
- Solids-free liquid wake
 - gas bubbles, 110–111
 - three-phase fluidized bed model, 107–108
- Sparger pressure drop, estimation, 90–91
- Sparger resistance, in bubble columns, 92–94
- Stability
 - bubble columns, 42–46, 78–88
 - fluidized beds, 26–27, 41–42, 91
 - gas–liquid bubble column maps, 61–65
 - gas–liquid bubble columns, 36–40
 - gas–solid fluidized bed maps, 46–60
 - gas–solid fluidized beds, 24–26, 32–36
 - MPC
 - asymptotic stability, 146
 - BIBO stability, 149–150
 - closed-loop stability, 157–159, 167–169, 185–186
 - definition, 145–146
 - FG stability, 150–152
 - finite-gain–initial conditions stability, 155
 - global asymptotic stability, 147
 - heavy oil fractionator, 165
 - input dependence, 153–155
 - inputs for characterization, 152–153
 - linear model, 170–172
 - nonlinear model, 172–174
 - nonlinear process, 162–163
 - p -norms, 149
 - proof and practice, 174–176
 - regions, 160–161
 - robust stability, 176–184
 - role in system, 155–156
 - uniform asymptotic stability, 147
 - uniform stability, 146
 - unstable CSTR, 148–149
 - unstable system, 147–148
 - multiphase systems, 23–24, 100–103, 114–115
 - solid–liquid fluidized bed maps, 46–60
 - solid–liquid fluidized beds, 32–36, 112–113
- State-space models, MPC, 189–191
- Steady-state conditions, solid–liquid fluidized beds, 12–15
- Stochastic disturbance model, MPC, 140
- Stochastic objective function
 - available measurements, 141
 - constraints, 141
 - MPC formulation, 140–141
 - sampling period, 141–142

T

- Terminal rise velocity, bubbles
 - in contaminated liquids, 43–44
 - estimation, 42
 - in gas–liquid bubble columns, 61
 - in pure liquids, 43
- Theory
 - MPC, 198–199
 - MPC classical control, 135–136
- Three-phase fluidized beds
 - characterization, 103–104

contraction–expansion prediction,
111–113
definition, 3–4
heuristic models, 105–109
parameter effects, 110–111

U

Unbounded dispersions
 bubble columns, 21–22
 criterion, 6–7
 fluidized beds, 18–20
 gas–liquid bubble columns, 18
 gas–solid fluidized beds, 15–18
 liquid–liquid spray columns, 18
 solid–liquid fluidized beds, 7–15
Uniform asymptotic stability, MPC, 147
Uniform stability, MPC, 146
Unstable process model, MPC, 140
Unstable system, MPC with bounded out-
 put, 147–148
Unstable units, MPC systems, 159–161

V

Velocity, in beds and columns
 slip velocity, 41, 44–45
 terminal rise velocity, 42–44, 61
 voidage propagation velocity, 29–30
 wave velocity, 27, 30–32
Virtual mass coefficient
 bubble columns, 46, 61–63
 fluidized beds, 41–42, 58
 in multiphase systems, 22
Voidage propagation velocity, fluidized
 beds, 29–30

W

Wake model, three-phase fluidized beds,
 105–109
Wave velocity, in beds and columns
 elastic, equations, 30–32
 kinematic, stability, 27