Guide to Selected Process Examples

APPENDIX G

Because of the strong interplay between process dynamics and control performance, examples should begin with process equipment and operating conditions. To this end, several process examples are introduced in the beginning chapters and used in many subsequent worked examples and questions. This approach has three advantages. First, the performance of different control approaches (e.g., tuning or control algorithm) can be evaluated on the same processes, allowing clear comparisons of competing methods. Second, the reader can concentrate on the learning objective applied to a familiar process. A final advantage is the reduction in the size of the book, since each example takes considerable space to introduce completely.

Since the reader may want to review the control approaches applied to a process, this guide is provided. Major worked examples and questions involving the most important processes are summarized in the tables. The symbols used in the tables are Ex for a worked example, Q for a question at the end of a chapter, S for a chapter section, F for a figure, and T for a table; as elsewhere, the number (or letter) before the period indicates the chapter (or appendix).

G.1 □ HEAT EXCHANGER

This is a simple model of a heat exchanger. Since the process fluid side is well mixed and the utility side is at quasi-steady state, the basic model is first-order, which allows some analytical solutions to be determined. See Table G.1.

TABLE G.1

Heat exchanger

	Key issue addressed		Key issue addressed
Q 1.9	Possibility for feedback control	F 14.2	Cascade control
F 3.9	Process schematic	F 15.5	Feedforward control
F 3.10	Linearization	Q 15.2	Cascade and feedforward control
Ex 3.7	Derive balances and linearized approximation	F 16.9	Valve characteristic
		Q 19.6	IMC controller design
Q 5.1	Multiple input changes	Ex I.1	Exchange with bypass
Q 5.2	Jacketed heat exhanger	Q I.1	Exchange with bypass
Ex 8.5	Analytical solution for proportional-integral feedback system	Q I.2	Exchange with bypass
		Ex L.8	Discrete model
		Ex L.9	Stability with digital PI
Ex 13.13	Process design for good performance	Ex L.11	Dynamics with digital PI

G.2 □ THREE-TANK MIXING PROCESS

The most often used process example is the three-tank mixing process. An important aspect of the process is its simplicity, allowing the reader to easily relate the design and operating parameters to its dynamic behavior. However, the process has been selected to elucidate many important factors in process control systems. This process is third-order and can be made unstable with a proportional-only controller; is mildly nonlinear and can show the acceptable range of linearization; does not conform to the first-order-with-dead-time model and can show the effects of structural errors in a model; and has dynamics that depend on operating conditions and can demonstrate the use of adaptive retuning.

In addition to those listed in Table G.2, the following topics address closely associated series of tanks: Q 15.2 on multitank heat transfer and Q 21.13 on loop pairing.

G.3 □ NONISOTHERMAL STIRRED-TANK CHEMICAL REACTOR (CSTR)

The nonisothermal CSTR is an important industrial process that introduces the opportunity for a diverse range of process dynamics. This example involves only a single, exothermic chemical reaction and can have stable over- and underdamped steady states as well as a locally unstable steady state(s). Also, important in the presentation control technology is the opportunity to investigate different pairings of manipulated and controlled variables in a multiloop control system.

The final sections in Table G.3 refer to Appendix C, which introduces some advanced topics in reactor dynamics and control.

G.4 □ TWO-PRODUCT DISTILLATION COLUMN

The previous processes were of low order, so they could be represented by a few differential equations. In addition to being an important industrial process, distillation is a high-order system whose linearized fundamental models are not normally analyzed. Also, the dynamic model formulation using the generalized tray concept is a worthwhile reinforcement to similar approaches covered in steady-state modelling. With two controlled compositions, the process offers a challenging two input–two output control system, when the control of pressure and levels is assumed. With no prior assumptions, the control design of a five input–five output system is a good control design case. To maintain simplicity, the case considered involves only binary distillation with constant relative volatility. In Table G.4, the cases not conforming to the exact parameters in Example 5.4 are marked with an asterisk (*).

G.5 ◻ TWO SERIES ISOTHERMAL CONTINUOUS STIRRED-TANK REACTORS (CSTR)

Additional low-order process examples are useful to reinforce principles. A series of two isothermal CSTRs is used throughout the book (see Table G.5) to provide many of these examples. Only one reaction occurs in each reactor, and the reactions are first-order. The model for this process is simple enough to enable the engineer to determine the effects of changes in equipment and operating parameters on the dynamics of the process and performance of the feedback control system.

TABLE G.2

Three-tank mixing process

	Key issue addressed		Key issue addressed
Ex 6.4	Process reaction curve	Q 11.9*a*	Execution period for digital control
Ex 7.2	Introduce the process model	S 13.5	Effect of model mismatch on closed-loop frequency response
S 8.4	Evaluate zero offset for P-only control		
S 8.5	Evaluate zero offset for I-only control	Q 13.1	Effect of process dynamics on performance and tuning
S 8.6	Evaluate zero offset for D-only control		
Q 8.2	Dynamic simulation	Q 13.13	Repeat stability, tuning, and performance analysis after process change
Q 8.12	Alternative process structure		
Ex 9.2	Tuning and performance	S 16.2	Effect of flow rate on tuning
Ex 9.3	Effect of disturbance time constant on closed-loop performance	S 16.3	Gain (tuning) scheduling
		Q 16.1	Effect of set point on tuning
Q 9.8	Dimensional analysis	Q 16.3	Ziegler-Nichols tuning
Ex 10.5	Roots of characteristic equation, root locus	Ex 19.3	IMC on third-order process
		Ex 19.4	IMC on approximate first-order-with-dead-time model
Ex 10.10	Ziegler-Nichols tuning		
Ex 10.18	Effect of model mismatch on stability analysis using Bode	Ex 19.6	IMC digital implementation and simulation
		Ex 19.7	IMC tuning correlations
Q 10.1	Effect on tuning of changing tank volume	Ex 19.8	IMC robustness
Q 10.11	The effect of process and control structures on possible dynamic responses	Ex 19.9	Smith predictor tuning and simulation
		Q 19.2	IMC tuning schedule
Q 10.17	Effect of adding dead time	Q 22.1	Variable-structure

TABLE G.3

Nonisothermal CSTR

	Key issue addressed		Key issue addressed
S 3.6	Dynamic behavior	Q 20.11	Integral controllability, loop pairing, and tuning for various sets ofdesign parameters
S 7.3	Selecting variables	F 22.5	Variable-structure control,
Q 7.1	Causal relationship	F 22.6	signal select
Q 7.9	Evaluate proposed single-loop feedback control structures	Ex 24.4	Dynamic transient exceeding steady-state operating window
Q 7.11*b*	Operating window	S C.1	Derivation of energy balance
Q 8.17	General behavior under P-only and PD control	S C.2	Modelling linearization
Q 10.11	Effect of process and control structure on possible dynamic responses	S C.3	Transfer function
Q 12.6	Failure modes	S C.4	Possibility of multiple steady states and their stability
Ex 13.12	Selecting manipulated variable	S C.5	Possibility of limit cycles
Q 13.14	Control performance	Q C.1	Modified process model
Ex 14.7	Cascade design	Q C.2	Transfer function
Q 14.11	Cascade design	Q C.3	Frequency response
Q 20.2	The effect of ΔH_{rxn} on multiloop stability and dynamic response	Q C.4	Empirical identification

TABLE G.4

Two-product distillation column

	Key issue addressed		Key issue addressed
Q 2.8*	Effect of distribution on profit	Ex 21.3	Effect of disturbance type on multiloop control performance
Q 2.9*	Effect of distribution on profit	Ex 21.6	Relative gain and loop pairings
S 5.6	Model development	Ex 21.9	Match tuning with performance goals
Ex 5.4	Simulated dynamic response	Ex 21.10	Decoupling, perfect and with model errors
Q 6.10	Process reaction curve	Q 21.1*	Tuning, loop pairing, performance and decoupling
Q 14.6*	Cascade control	Q 21.8*	Tuning, loop pairing, performance and decoupling
Ex 15.7*	Feedforward control	Q 21.11*	Control loop pairing
S 17.5*	Inferential tray temperature	Ex 23.1	Complexity of analytical inverse
Ex 20.2	Linearized model	Ex 23.6	DMC control
Ex 20.4	Operating window	Ex 23.8	QDMC control
Ex 20.5	Evaluation of controllability	Appendix J	Control Design
Ex 20.7	Effect of interaction on the changes in manipulated variable		
Q 20.9*	Controllability, interaction, tuning		
Q 20.15*	Controllability, interaction, tuning		
Ex 21.2	Effect of control structure on multiloop control performance		

G.6 HEAT EXCHANGE AND FLASH DRUM

A flash drum at controlled pressure and temperature is a simple method for effecting a physical separation of components with different vapor pressures. This process provides the opportunity to evaluate inferential control and pair loops for dynamic performance. See Table G.6.

TABLE G.5

Two isothermal CSTRs

	Key issue addressed		Key issue addressed
Ex 3.3	Derive process model and evaluate a step response	Q 9.10	Effect of changing temperature on tuning
Q 3.14	Pulse response	Ex 10.4	Roots of closed-loop characteristic equation (modified process)
Ex 4.6	Solve step response using Laplace transforms (slightly modified model)	Ex 10.8	Repeat Ex 10.4 with additional dead time
Ex 4.8	Stability		
Ex 4.9	Derive the transfer function	Q 10.11	Effect of process and control structure on possible dynamic responses
Ex 4.11	Damping		
Ex 4.12	Block diagram	Ex 13.8	Effect of inverse response on control performance
Ex 4.16	Frequency response		
Q 4.1	Emergency response	Q 13.18	Effect of an alternative manipulated variable on control performance
Q 4.7	Modified inputs		
Q 4.16	Derive model and dynamic response for a different input variable	Q 15.11	Effect of dynamics on feedforward-feedback control
Q 5.4	Four series reactors	Q 21.10	Multiloop control
Q 7.3	Causal relationship	Ex I.2	Model with solvent flow adjusted
Q 7.11*c*	Operating window	Q I.3	Model with F_A adjusted
Q 8.15	Loop behavior	Q I.4	Control design

TABLE G.6

Heat exchange and flash drum

	Key issue addressed		Key issue addressed
Q 1.6	Control system components	Ex 24.5	Degrees of freedom
S 2.2	Control objectives	Ex 24.6	Controllability
S 17.2	Inferential variable evaluation	Ex 24.7	Operating window
Q 17.2	Model analysis	Ex 24.8	Loop pairing
Q 17.12	Controllability	Ex 24.9	Algorithm selection and tuning
Q 21.5	Loop pairing	Ex 24.10	Control for safety
T 24.1	Control design form (CDF)	Ex 24.11	Process monitoring
Ex 24.1	Sensors	Ex 24.12	Dynamic performance
Ex 24.2	Control objectives	Q 24.22	Partial control
Ex 24.3	Final elements		