## Chemical Process Control References and Endnotes

Non-crucial footnotes and comments are placed here. The reference list is relatively short. It is prepared for a student, not for a faculty. The main references are restricted to introductory control texts. We have eliminated more advanced texts, texts that are not widely adopted, and older texts written before you were born. We only include a handful of research articles that are readable in an introductory topic. Here are some recommended resources by chapter. Their references are listed in the last section.

### 1. Introduction

Our Primer has a three-page introduction, which is more succinct than virtually all texts. If you need a thorough introduction, see, for example, Ogunnaike and Ray (1994; Chaps. 1-2), Marlin (1995; Chaps 1-3), and Luyben and Luyben (1997; Chaps. 1, and 4-6).

### 2. Mathematical background

If you need help on Laplace transform and ordinary differential equations, refer to your old ODE text first since you paid for that already. Otherwise, every single introductory text covers these topics. The writing quality varies widely. Among the best is still Stephanopoulos (1984). Since you are finding a second material to supplement our Primer, which text to pick becomes less critical. In other words, we have no favorites, and almost any text will do. By and large, the organization of the Primer follows the more traditional approach of Stephanopoulos (1984), Seborg, et al. (1989; Chaps. 3-6), and Smith and Corripio (1997, Chaps. 3 and 4).

*Notes*:

- The example in Section 2.8.1 is adapted from Seborg *et al.*, Example 3.7.
- In Section 2.10, we did not cover **Mason's gain formula** and **signal flow graph**. To read about it, you need one of the texts such as Kuo (1995), Ogata (1997), and Phillips and Harbor (2000). A signal flow graph is an alternate representation of a block diagram with each variable, such as R, E and Y, represented by a dot (node) and a block replaced by a line (a branch). The Mason's gain formula helps to derive transfer functions, and we can consider it as a generalization of our simple feedback loop to more complex problems. The idea to have a formula sounds attractive, but we can easily be miss-counting terms and the procedure must be applied with extreme care. If we are not careful, heavy reliance on the formula may create more confusion (and mistakes!) than utility. The first two examples that we have are very tricky if you try to apply Mason's formula. You stand a much better chance to getting it right by using the simple algebraic approach that we have chosen.

### 3. Process modeling

In Chemical Engineering, our training on modeling starts with Felder and Rousseau (Elementary Principles of Chemical Processes, 3rd ed. Wiley, 2000) and you should be familiar with that. In most control texts, you should find materials or process modeling examples that make use of mass and energy balances. Aside from standard texts, Corripio (1998) is a very unusual book that is based on workshops and has model descriptions of a very comprehensive set of chemical processes.

Another important class of models is electromechanical systems. They involve mechanical systems with translational and/or rotational motions and electric motors. Among the introductory texts, Kuo (1995, Chap. 4) has the most thorough explanation starting from basic physical principles. Phillips and Harbor (2000, Chap. 2) have a reasonably good introduction. Franklin *et al*. (1994) do not have much basic details, but they have the most real life relevant and interesting examples.

*Notes*:

- In some mechanical or electrical engineering texts (e.g. Kuo's), $\zeta/\tau$ is named the damping factor. Ignore this as it can only cause confusion.
- In terms of terminology, referring $\zeta$ to as damping coefficient probably makes the most sense, and damping ratio the least. Inexplicably, most people call $\zeta$ a ratio, and so do we in perpetuating this poor lexicon.

## 4. Model identification

Several texts contain some introductory material regarding process or model identification. They are Seborg, et al. (1989; Chap. 7), Ogunnaike and Ray (1994; Chaps. 12, 13), and Marlin (1995; Chap. 6).

## 5. PID controllers tuning and stability analysis

Similar to the comment that we made in mathematical background section, all introductory texts cover PID controller tuning techniques. The writing quality and style vary and you just have to find one that suits you for a second source. In addition to the fundamental concepts, several texts offer insights on tuning and practical implementation: Smith and Corripio (1997, Chaps. 6-9), Corripio (1998), Riggs (1999; Chaps. 7, 11), and in Marlin (1995) spread over many chapters.

*Notes*:

- Tuning relations for minimum ISE and IAE criteria can be found in Smith and Corripio (1997, Chap. 7).
- There are many papers that attempt to find improved tuning techniques. One example is the short note by Lee, et al. (1990), which is chosen for its readability.
- A good extension of the more routine modeling analysis and controller design is the incorporation of a recycle stream in the process. A good reference is Luyben (1993).
- We mentioned external feedback in a footnote but offered no reference. We can find that in Marlin (1995, Chap. 12).
- The analysis of IMC can be complicated. There are two articles that a beginning student can try. One is a non-technical overview by Chien and Fruehauf (1990). The second is the crucial work of Rivera, et al. (1986), which showed how IMC analysis can lead to PID type controllers.
- We mentioned the sensitivity problem in the final remarks of Chapter 7. You may find the explanation of sensitivity in Ogata (1997, Chap. 10), and Phillips and Harbor (2000, Chap. 9).
- There is much more to designing lead-lag compensators than Example 8.14. For a formal discussion, see for example, Kuo (1995, Chap. 10), and Ogata (1997, Chaps. 7, 9).
- We omitted the general formula for an *n*-th order Routh array. It can be found in all older texts such as Seborg, et al. (1989; Chap. 11), and Ogunnaike and Ray (1994; Chap. 14). Our fourth order example is sufficient to provide the basic idea. With a fourth order system, we can handle a fourth order process with proportional control, or a third order process with PID control.

## 6. Control hardware

Control hardware such as valves and sensors is missing from our Primer. The best description is probably Smith and Corripio (1997, Chap. 5 and Appendix C). Also good are Riggs (1999; Chap. 2) and Luyben and Luyben (1997; Chap. 3). This topic is also where more “nuts and bolts” practical handbooks are useful. (A handful is listed at the end of the References.)

Smith and Corripio (1997; Appendix A), and Ogunnaike and Ray (1994; Appendix A) also cover control system symbols in process and instrumentation diagrams. For formal industrial standards, one should consult the International Society for Measurement and Control (ISA, www.isa.org).

### 7. Multiloop systems

A good many chapters and pages are needed to cover the topics thoroughly. See, for example, Seborg, et al. (1989; Part Five), Ogunnaike and Ray (1994; Chaps. 20-22), Marlin (1995; Parts IV and V), and Smith and Corripio (1997, Chaps. 10-13).

With articles, Witcher and McAvoy (1977) is an old but crucial article in explaining multivariable interactions. Finally, Krishnaswamy, et al. (1990) and Lipták (1986) are two relatively "non-technical" articles on multiloop systems.

*Notes*:

- For your information, the Smith predictor is really old (O.J. Smith, *Chem. Eng. Prog.* **53**, 217, 1957), being discovered before the computer age.
- An additional comment regarding ratio control. In a more general design, we'd consider the fuel gas flow rate to be a load variable or a so-called "wild stream" that we can measure but cannot control (a scenario common in blending processes). We can also first calculate the ratio of the two flow rates, and compare the ratio with the desired ratio (the set point) in a ratio controller. The output of this controller then manipulates the air flow rate. A more detailed discussion can be found in Smith and Corripio (1997).
- In an off-handed way, we mentioned one may use singular value analysis on the steady state gain matrix. One may find a brief explanation and associated references in Seborg, et al. (1989; Chap. 28).

### 8. State space control

This is an important topic that is sorely missing in all chemical introductory texts. All the electrical and mechanical texts cover this material. Some texts, for example Kuo (1995), actually blend classical and state space control together, which may make learning more difficult in a quarter-long course. Otherwise, see Ogata (1997; Chaps. 3, 4, 11, 12), and the more compact writing of Phillips and Harbor (2000, Chaps. 3, 9) and Franklin, et al. (1994; Chaps. 2, 7). Among introductory texts, Ogata arguably has the most thorough explanation of state space analysis. Our Primer is less comprehensive than these texts. We do what we should, which is to provide a non-intimidating initial coverage of only the most important features.

*Notes*:

- Comment on Eq. (4-15). If you are curious, there are different ways to find the coefficients of the closed-form expansion of the exponential function. For example, one can make use of Lagrange’s interpolation, which leads to Sylvester’s interpolation formula. Or we can invoke the remainder form of matrix functions as a result of applying the Cayley-Hamilton theorem. Details can be found in Ogata (1997).
- More detailed explanation and analysis of observability matrix Eq. (9-12) and all other topics in Chapter 9 can also be found in Ogata (1997).

### 9. MATLAB Aids

The reference list includes some texts that make use of MATLAB and Doyle (2000), which really is a manual of some SIMLINK teaching modules. To learn and use MATLAB, the best resource is probably MATLAB's Help Desk, and if you are comfortable in using that, you don't need any of the books listed below.

## References

### • Introductory texts for Chemical Engineering

In this group, the more recent texts are Smith and Corripio (1997), Luyben and Luyben (1997), and Riggs (1999). Stephanopoulos (1984) is rather old, but its clarity and precise writing is still unmatched. Seborg, et al. (1989) is still widely adopted. As for Bequette (2003), it has a strong chapter on IMC.

1. B. W. Bequette, *Process Control: Modeling, Design And Simulation*, Upper Saddle River, New Jersey: Prentice Hall, 2003.
2. A. B. Corripio. *Design and application of process control systems*, 2nd ed. Research Triangle Park, NC: ISA, 1998.
3. D. R. Coughanowr. *Process Systems Analysis and Control*, 2nd ed. New York: McGraw-Hill, 1991.
4. M. L. Luyben and W. L. Luyben. *Essentials of process control*, New York: McGraw-Hill, 1997.
5. T. E. Marlin. *Process Control: Designing Processes and Control Systems for Dynamic Performance*, New York: McGraw-Hill, 1995.
6. B. A. Ogunnaike and W. H. Ray. *Process Dynamics, Modeling and Control*, New York: Oxford University Press, 1994.
7. J. B. Riggs. *Chemical Process Control*, Lubbock, Texas: Ferret Publishing, 1999.
8. D. E. Seborg, T. F. Edgar, and D. A. Mellichamp. *Process Dynamics and Control*, New York: John Wiley, 1989.
9. C. A. Smith and A. B. Corripio. *Principles and Practice of Automatic Process Control*, 2nd ed. New York: John Wiley, 1997.
10. G. Stephanopoulos. Chemical Process Control. *An Introduction to Theory and Practice*, Englewood Cliffs, N.J.: Prentice Hall, 1984.

### • Introductory texts for Electrical and Mechanical Engineering

All five texts listed below are well written and widely used. Anyone may serve as a good second source reading, especially regarding state space control.

1. R. C. Dorf. *Modern control systems*, 8th ed. Menlo Park, Calif.: Addison-Wesley, 1998.
2. G. F. Franklin, J. D. Powell, and A. Emami-Naeini. *Feedback Control of Dynamic Systems*, 3rd ed. Reading, Mass.: Addison-Wesley, 1994.
3. B. C. Kuo. *Automatic Control Systems*, 7th ed. Englewood Cliffs, N.J.: Prentice Hall, 1995.
4. K. Ogata. *Modern Control Engineering*, 3rd ed. Upper Saddle River, N.J.: Prentice Hall, 1997.
5. C. L. Phillips and R. D. Harbor. *Feedback control systems*, 4th ed. Upper Saddle River, N.J.: Prentice Hall, 2000.

### • Secondary References

Shinskey (1988) is a classic that you should know that it exists. If you need to learn more about implementation issues and practical aspects of PID controllers, including autotuning techniques, the best source is Åstrom and Hägglund (1995). The writing of this book is lucid and understandable to a beginner even though the authors did not target readers of an introductory course. The model-based text by Brosilow and Joseph begins with introductory material, but we believe it is better suited for a second course.

1. C. Brosilow and B. Joseph, *Techniques of Model-based Control*, Upper Saddle River, New Jersey: Prentice Hall, 2002.
2. K. J. Åström and T. Hägglund. *PID Controllers*, 2nd ed. Research Triangle Park, North Carolina: ISA, 1995.
3. F. G. Shinskey. *Process Control Systems. Application, Design, and Tuning*, 3rd ed. New York: McGraw-Hill, 1988.

**• MATLAB related texts and tutorials**

This is just a sampling of the large collection of MATLAB aides. The list is short since we have eliminated most entries that came out before 1995. MATLAB has gone through such significant changes over the years that you should only rely on aides that address Version 5.

1. T. E. Djaferis. *Automatic control: The power of feedback using MATLAB*, Pacific Grove, CA: Brooks/Cole, 2000.
2. F. J. Doyle III. *Process control modules: A software laboratory for control design*, Upper Saddle River, N.J.: Prentice Hall, 2000.
3. D. C. Hanselman and B. C. Kuo. *MATLAB tools for control system analysis and design*, 2nd ed. Englewood Cliffs, N.J.: Prentice Hall, 1995.
4. B. J. Lurie. *Classical feedback control with MATLAB*, New York: Marcel Dekker, 2000.
5. K. Ogata. *Designing linear control systems with MATLAB*, Englewood Cliffs, N.J.: Prentice Hall, 1994.
6. K. Ogata. *Solving control engineering problems with MATLAB*, Englewood Cliffs, N.J.: Prentice Hall, 1994.
7. N. E. Leonard and W. S. Levine. *Using MATLAB to analyze and design control systems*, 2nd ed. Redwood City, CA: Benjamin/Cummings, 1995.

**• Journal articles**

These articles deal with classic controller designs. See the comments above on what each is about.

1. I. L. Chien and P. S. Fruehauf. "Consider IMC tuning to improve controller performance," Chem. Eng. Prog. 33-41 (Oct., 1990).
2. P. R. Krishnaswamy, G. P. Rangaiah, R. K. Jha, and P. B. Deshpande. "When to use cascade control," IEC Res. **29**: 2163-6 (1990).
3. J. Lee, W. Cho, and T. F. Edgar. "An improved technique for PID controller tuning from closed-loop tests," AIChE J. **36**: 1891-5 (1990).
4. B. G. Lipták. "Controlling and optimizing chemical reactors," Chem. Eng. 69-81 (May 26, 1986).
5. W. L. Luyben. "Dynamics and control of recycle systems. 1. Simple open-loop and closed-loop systems," IEC Res. **32**: 466-75 (1993).
6. D. Rivera, S. Skogestad, and M. Morari. "Internal model control: 4. PID controller design," IEC Proc. Des. Dev. **25**: 252-65 (1986).
7. M. F. Witcher and T. J. McAvoy. "Interacting control systems: Steady state and dynamic measurement of interaction," ISA Trans. **16**: 35-41 (3, 1977).

**• Practical reference handbooks**

1. G. K. McMillan, and D. M. Considine (Eds.) *Process/Industrial Instruments and Controls Handbook,* 5th Edition, New York: McGraw-Hill, 1999.
2. N. A. Anderso. *Instrumentation for Process Measurement and Control*, 3rd Edition, Boca Raton, Florida: CRC Press, 1997.
3. B. G. Liptak (Ed.) *Process Control Instrument Engineers' Handbook*, 3rd Edition, New York: CRC Press, 1995.
4. J. G. Webster (Ed.) *The Measurement, Instrumentation and Sensors Handbook*, New York: CRC Press, 1998.