the amplitude ratio of the measured variable to the disturbance. Recall that only the measured variable is known to the plant personnel, discuss the differences in the results and their importance in analyzing plant performance.

**13.17.** The transfer function between the set point and the controlled variable is given in equation (13.4). Apply the following controller design method to arrive at an algorithm other than PID. Assume the input-output response is defined at some good performance [i.e., $CV(s)/SP(s) = T(s)$ is specified]. Solve for the controller transfer function that would give this performance. Discuss whether this controller can be implemented in analog or digital form.

**13.18.** The process design in Example 13.8 with a parallel structure is considered in this question. The concentration at the outlet of the second reactor is to be controlled as in Example 13.8, except that the flow rate of stream A (not the solvent) is to be manipulated.

(*a*) Based on the different dynamics between the manipulated and controlled variables, predict the control performance and whether it would be better than the system in Example 13.8. (Hint: The results from end-of-appendix question I.3 will help in answering this question.)

(*b*) Develop a dynamic simulation for this design, tune the feedback PI controller, and compare the control performance with Example 13.8.

**13.19.** The process with recycle was analyzed in end-of-chapter question 5.14. Determine the value of the recycle for which a feedback PI control system, controlling the outlet composition $C_{A2}$ by adjusting $C_{A0}$, would give the best performance.

**13.20.** Chemical reactors were analyzed in question 5.7 for two different reaction kinetics. For both kinetics (answered separately), determine which feedback control system, controlling $C_A$ or $C_B$ by adjusting $C_{A0}$, would provide the best performance. Base your answer entirely on the feedback dynamics, not the process gain.

# Enhancements to Single-Loop PID Feedback Control

PART

# IV

As we have seen, single-loop PID feedback control often provides good control performance and always yields zero steady-state offset for steplike inputs. The controller is easy to use, because the PID control algorithm can be applied on nearly all processes without alteration. The performance is very good, considering the little information required for design and tuning. As might be expected, the simplicity of the PID controller, while reducing engineering effort and computer calculations, results in control performance that is not always the best possible. The key advantages and disadvantages of single-loop feedback control are summarized in Table IV.1. The methods in Part IV are designed to partially overcome these disadvantages.

The best approach for improving control performance is to eliminate or reduce the disturbances by improving the operation of upstream processes. The next best solution is to eliminate the difficult factors from the feedback dynamic responses by changing the process design. For example, the dead time could be reduced by relocating sensors or eliminating sample systems by placing the sensor *in situ*. If the dead time could be reduced sufficiently, much improved control performance could be achieved. However, changing the process design is not always possible or the best economic decision.

We assume here that all reasonable process modifications have been made and that further enhancements are to be achieved through control modifications. To improve the feedback performance, the controller design must be changed in a manner that takes advantage of additional knowledge about the process dynamics or control objectives through one or more of the following steps:

**TABLE IV.1**

**Summary of single-loop feedback control**

| Advantages | Disadvantages |
|---|---|
| Achieves zero steady-state offset for all step-like inputs | Process output must be upset before feedback action begins. |
| Uses only one measurement | Feedback control performance can be poor for some combinations of disturbance frequencies and feedback dynamics. |
| Algorithm and tuning rules available | Poor feedback can cause instability. PID does not provide the best possible control for all processes. |

- Use additional measures of process outputs.
- Use additional measurements of the process inputs.
- Use explicit modelling in the control calculation.
- Modify the PID algorithm and tuning to match the control objective.

To achieve enhancements the engineer requires additional process insight, which is developed though increased engineering analysis and effort. The additional effort can be richly rewarded, because the enhancements can substantially improve control performance, reducing the integral errors and maximum deviations by more than a factor of ten, in some situations. The success of the enhancement depends on the quality of the engineering analysis—that is, the accuracy of the process insight and the application of the design principles. It is important to remember that regardless of the complexity of the enhancements, feedback control from the controlled variable should always be retained (when the sensor exists) so that zero steady-state offset is achieved.

Several control enhancements are presented in this part of the book. They were chosen based on the following criteria:

- *Reinforce principles.* Each of these enhancements partially overcomes one or more of the causes for poor control performance. Thus, we have the opportunity to reconsider these process-related limitations as we learn how an enhancement improves performance. This perspective is important because the enhancements are designed based on sound control theory and are not a collection of "ad hoc tricks."
- *Demonstrate practice.* The enhancements are some of the most frequently applied designs in the process industries and can be implemented in commercial control equipment at low cost.
- *Apply process insight.* The proper use of the enhancements requires sound understanding of dynamics and operating goals of the process. Thus, this part

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strengthens our understanding of how the process equipment and operating conditions influence designs to achieve specified control performance.

Each enhancement is briefly summarized in Table IV.2; the reader may find it helpful to refer to this table after covering each chapter in this part.

The single-loop enhancements covered in this part are used widely in process control. They become especially important when designing control strategies for complex units with many controlled variables, sensors, and final control elements. Therefore, it is essential that the student master these enhancements before progressing to the more advanced, multivariable design topics.

**TABLE IV.2**

**Summary of single-loop control enhancements**

| Enhancement | Key issue | New input measurement | New output measurement | Process modelling | Standard or modified PID | New control algorithm |
|---|---|---|---|---|---|---|
| Cascade | Feedback dynamics | | X | | X | |
| Feedforward | Feedback dynamics | X | | | | X |
| Nonlinear processes | Changing process dynamics | X | | X | X | |
| Inferential | Lack of online sensor | | X | X | X | |
| Level | Different control objective | | | | X | |
| Predictive control | Complex feedback dynamics | | | X | | X |