Process Dynamics

PART II

The engineer must understand the dynamic behavior of a physical system in order to design the equipment, select operating conditions, and implement an automation technique properly. The need for understanding dynamics is first illustrated through the discussion of two examples. The first involves the dynamic responses of the bus and bicycle shown in Figure II.1. When the drivers wish to maneuver the vehicles, such as to make a 180° U turn, the bicycle can be easily turned in a small radius, while the bus requires an arc of considerably larger radius. Clearly, the design of the vehicle affects the possible maneuverability, even when the bus has an expert driver. Also, the driver of the bus and the rider of the bicycle must use different rules in steering. This simple example demonstrates that (1) a key aspect of automation is designing and building equipment that can be easily controlled, and (2) the design and implementation of an automation system requires knowledge of the dynamic behavior of the system.

These two important principles can be applied to the chemical reactor example shown in Figure II.2. The reactor operation can be influenced by adjusting the opening of the valve in the coolant pipe, and the outlet concentration is measured by an analyzer located downstream from the reactor outlet. Regarding the first principle (the effect of process design), it seems likely that the delay in measuring the outlet concentration would reduce the effectiveness of feedback control. Regarding the second principle (the effect of automation method), a very aggressive method for adjusting the coolant flow could cause a large overshoot or oscillations in returning the concentration to its desired value; thus, the feedback adjustments should be tailored to the specific process.

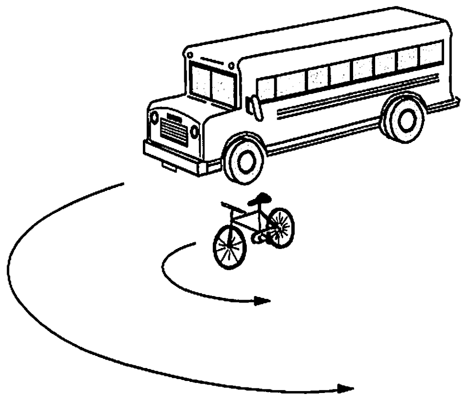

FIGURE II.1

Bus and bicycle maneuverability.

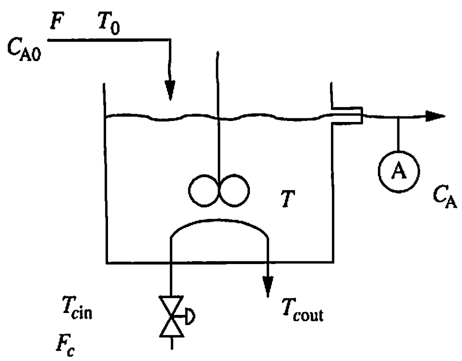

FIGURE II.2

Nonisothermal CSTR.

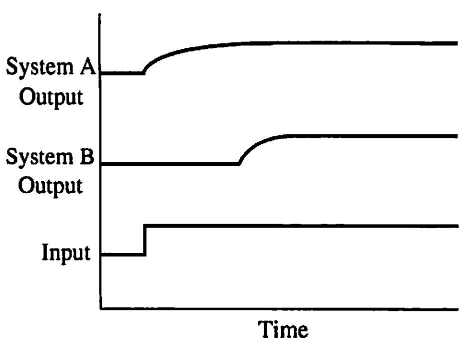

FIGURE II.3

The knowledge of dynamic behavior required for process control is formalized in mathematical models. In fact, modelling plays such a central role in the theory and practice of process control that the statement is often made that modelling is the key element in the successful application of control. A complete explanation of the needs of process control cannot be presented until more detail is covered on feedback systems; however, the importance of the four basic questions to be addressed through modelling should be clear from the general discussion in the previous chapters, along with the examples in Figures II.1 and II.2.

1. *Which variables can be influenced?* Process control inherently involves some manipulated variables, which can be adjusted, and some controlled variables, which are affected by the adjustments. By turning the steering wheel, the driver can influence the direction of the bus, but not its speed. By changing the coolant valve opening in the reactor example, the reactor temperature and concentration can be influenced. The identification of variables will be addressed in this part through the analysis of degrees of freedom and cause-effect relationships, and the aspect of controllability will be introduced later in the book.
2. *Over what range can the variables be altered?* The acceptable range of process variables, such as temperature and pressure, and the limited range of the manipulated variables places bounds on the effects of adjustments. The bus wheels can only be turned a maximum amount to the right and left, and the coolant valve is limited between fully closed (no flow) and fully opened (maximum flow). The range of possible values is termed the *operating window*, and models can be used to determine the bounds or "frame" on this window quantitatively.
3. *How effectively can feedback maintain the process at desired conditions?* The following aspects of the process behavior are required to implement process control.
   (*a*) *Sign and magnitude of response:* The bus driver must know how the bus will respond when the wheel is turned clockwise, and the operator needs to know whether temperature will increase or decrease when the valve is opened. It is essential that the sign does not change and is best if the magnitude does not vary greatly.
   (*b*) *Speed of response:* The speed must be known to determine the manipulations that can be entered; if the manipulations are too aggressive, the system can oscillate and even become unstable. This can happen in driving a bus on a slippery road and in trying to control the concentration when there is a long delay between the adjusted variable and measurement.
   (*c*) *Shape of response:* The shape of dynamic responses can vary greatly. For example, the two responses in Figure II.3 have the same "speed" as measured by the time to reach their final values, but the shapes are different. Response A, which gives an indication of the response without delay, is better for control than response B, which gives no output indication of the input change for a long time.
4. *How sensitive are the results?* Process control systems are usually applied in industrial-scale plants that change operations often and experience variation

in operating conditions and equipment performance. This variation affects the dynamic behavior of the process, the items in the preceding question, which must be considered in process control. For example, the behavior of the chemical reactor could depend on an inhibitor in the feed and catalyst deactivation. The analysis of the possible variation in the system and sensitivity of the dynamic behavior to the variability begins in the modelling procedure.

In summary, the dynamic features most favorable to good control include (1) nearly constant sign and magnitude, (2) a fast response, (3) minimum delay, and (4) insensitivity to process changes. This good situation cannot always be achieved through process design, because processes are designed to meet additional requirements such as high pressures, volumes for reactor residence times, or area for mass transfer and heat transfer. However, the features that favor good control should be a consideration in the process design and must be known for the design of the process controls.

The modelling procedures in this part provide methods for determining these features and for relating them to process equipment design and operating variables. There are many types of models used by engineers, so important aspects of these models used in this book are briefly summarized and compared with alternatives.

1. *Mathematical models:* The following definition of a mathematical model was given by Denn (1986).

   > A mathematical model of a process is a system of equations whose solution, given specific input data, is representative of the response of the process to a corresponding set of inputs.

   We will deal exclusively with mathematical models for process analysis. In contrast, experimental or analog methods can use physical models, like a model airplane in a wind tunnel or an electrical circuit, to represent the behavior of a full-scale system empirically.
2. *Fundamental and empirical models:* Fundamental models are based on such principles as material and energy conservation and can provide great insight as well as predictive power. For many systems, fundamental models can be very complex, and simplified empirical models based on experimental dynamic data are sufficient for many process control tasks. Both types of models are introduced in Part II.
3. *Steady-state and dynamic models:* Both steady-state and dynamic models are used in process control analysis. Dynamic modelling is emphasized in this book because it is assumed that the reader has prior experience in steady-state modelling.
4. *Lumped and distributed models:* Lumped models are valid for systems in which the properties of a system do not depend on the position within the system. For lumped systems, steady-state models involve algebraic equations, and dynamic models involve ordinary differential equations. Distributed models are valid for systems in which the properties depend on position, and their dynamic models involve partial differential equations. To maintain a manage-

able level of mathematical complexity, essentially all models in this book will involve lumped systems, with the exception of a model for pure transportation delay in a pipe. Since many chemical process designs involve inventories that are approximately well-mixed, lumped models are often sufficient, but each system should be evaluated for the proper modelling assumptions.

Finally, one must recognize that modelling is performed to answer specific questions; thus, no one model is appropriate for all situations. The methods in this part have been selected to provide the information required for the control analyses included in this book and provide only a limited introduction to the topic of process modelling. Many interesting modelling concepts, mathematical solution techniques, and results for important process structures are not included. Therefore, the reader is encouraged to refer to the references at the end of each chapter.

REFERENCE

Denn, M., *Process Modeling*, Pitman Publishing, Marshfield, MA, 1986.