

**Process Control**

**Pressure, Flow, and Level  
Processes**

**Course Sample**

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






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# Safety and Common Symbols

The following safety and common symbols may be used in this course and on the equipment:

Symbol	Description
	<b>DANGER</b> indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	<b>WARNING</b> indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	<b>CAUTION</b> indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	<b>CAUTION</b> used without the <i>Caution, risk of danger</i> sign  , indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, risk of electric shock
	Caution, lifting hazard
	Caution, hot surface
	Caution, risk of fire
	Caution, risk of explosion
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation

# Safety and Common Symbols

Symbol	Description
	Consult the relevant user documentation.
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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# Preface

The growing use of process control in all types of industry comes from the need for a fast, low-cost means of production with better quality, less waste, and increased performance. Process control provides many other advantages, such as high reliability and precision at a low cost. Taking advantage of computer technology, controllers are more efficient and sophisticated than ever. To successfully operate and troubleshoot process control systems, effective training on process control systems is essential.

The curriculum using the Process Control Training System is divided into three courses that respond to the various training needs in the field of instrumentation and process control. All three courses use water as the process medium.

The main objective of the basic course is to teach the operating principles, measurement and control of pressure, flow, and level processes. In addition, students gain valuable experience tuning closed-loop processes using the most frequently encountered industrial methods. Only basic equipment is required for this course, but the industrial pressure, flow, and level add-on can be used to complement the learning experience.

The second course is similarly designed but concentrates on temperature processes. In addition to the basic equipment, the temperature add-on is necessary. An industrial heat exchanger add-on is optional.

The third course is structured like the first two, but focuses on pH processes. This time, the basic equipment and the pH add-on are mandatory.

Processes can be controlled using the Process Control and Simulation Software (LVProSim) or an optional PID controller. The exercises in the manual have been written for 4-20 mA control signals, but they can be easily adapted for 0-5 V signals. The experiments are performed using the I/O interface of the LVProSim controller with 4-20 mA signals. However, they can also be accomplished with other PID controllers and previous versions of the LVProSim I/O interface.

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to [services.didactic@festo.com](mailto:services.didactic@festo.com).

The authors and Festo Didactic look forward to your comments.



# About This Course

## **Manual objectives**

When you have completed this manual, you should be able to:

- explain the basic principles related to pressure, flow, and level measurement.
- name the different pressure, flow, and level measurement devices.
- understand the physical principles behind the various measurement devices.
- read and understand flow diagrams and wiring diagrams.
- perform pressure, flow, and level measurements.
- characterize pressure, flow, and level processes.
- perform control on pressure, flow, and level processes.
- understand the basic theory of centrifugal pumps.

## **Safety considerations**

Safety symbols that may be used in this course and on the equipment are listed in the Safety and Common Symbols table at the beginning of this document.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

## **Systems of units**

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).





# To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

## **Accuracy of measurements**

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

The instructor should be familiar with process measurement and control to recognize erroneous results. It is advised that a complete run-through of each exercise be included in the instructor's preparation for class.

The training system can be controlled by using the included Process Control and Simulation Software (LVProSim) or with a trend recorder and any other conventional PID controller compatible with 4-20 mA or 0-5 V signals. For the sake of simplicity, the exercises in the Student Manual Temperature Process Control and their solutions have been written for a controller that works with 4-20 mA signals, which is the case of the LVProSim controller. If a controller that works with 0-5 V signals is used, the instructor should adapt the exercises in consequence prior to their beginning by the students.



Sample  
Extracted from  
Instructor Guide



## Process Characteristics

### UNIT OBJECTIVE

When you have completed this unit, you will be able to understand the dynamics of process control systems. You will know the difference between open-loop and closed-loop processes. You will also be able to characterize a process.

### DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Dynamics
- Types of processes
- Process characteristics

### DISCUSSION OF FUNDAMENTALS

#### Dynamics

In a dynamical system, actions that the various devices (or the operator) perform do not have an instantaneous effect on the system. There is a delay between the action and the effect of this action on the system. Illustrations of this principle can be observed in many situations of everyday life. In your house, turning on the hot water faucet does not provide hot water immediately. Sometimes the water in the pipe has cooled down and you have to wait for hot water to come all the way from the water heater to the faucet. Similarly, when a car driver applies the brakes, the car does not come to a stop immediately.

How dynamical systems respond to an action is determined by many factors. However, as far as process control is concerned, we can divide these factors in three categories: resistance, capacitance, and inertia.

#### *Resistance*

Most processes have some **resistive part**. The resistive parts of a system oppose the transfer of energy or mass. An example of **resistance** encountered in a process control system is the pressure loss that pipes and instruments cause. A half-opened valve along a pipe line is a resistance. Changing the load of this resistance (i.e., the valve opening) produces an immediate and proportional change in the flow rate. Reducing the valve opening slows the flow rate of the liquid in the pipe. Processes that consist only of resistive elements are called resistance-type processes or proportional only processes. Figure 5-1 shows a purely resistive process.

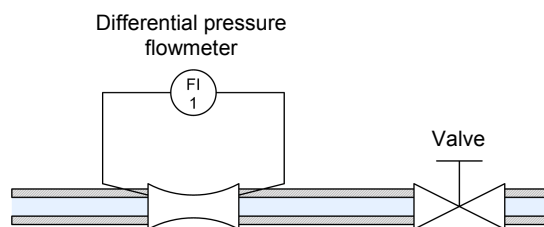


Figure 5-1. Purely resistive process.

### Capacitance

In an electrical circuit, a **capacitance** is an element that can accumulate electrical energy. The capacitor takes a certain amount of time to charge, it stores a given amount of energy as an electric field, and this energy is given back to the system later. Capacitance in a process control system is similar to capacitance in an electrical circuit. It has the ability to store either energy or material. The simplest type of capacitive element in a process control system is a liquid storage tank with an inflow. Figure 5-2 shows such a tank installation. In this example, the storage tank accumulates water and the level rises at a rate inversely proportional to the tank capacitance. If the resistance in the inflow is neglected, this is an example of a purely capacitive process in terms of level (not flow). Similar to an electric capacitor, the tank stores water and the rate at which the level rises is inversely proportional to the capacitance of the tank.

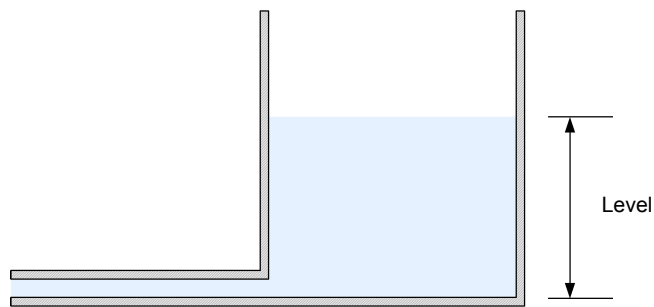


Figure 5-2. Purely capacitive process.

### Inertia

**Inertia** has a minimal effect on the response of most process control systems with few mechanical parts. However, the effect of inertia is sometimes non-negligible in flow systems that accelerate or decelerate large quantities of fluid.

### Types of processes

Process control is concerned with the evolution of systems with time. Therefore, the best way to classify a process is to observe the evolution of the output variable when there is a **step change** in the input variable. By observing the shape of the curve of the output variable as a function of time you can usually determine which type of process it is. Figure 5-3 shows how you can use a step change to obtain the **response curve** of a process. The shape of the system response to the step change determines the type of process.

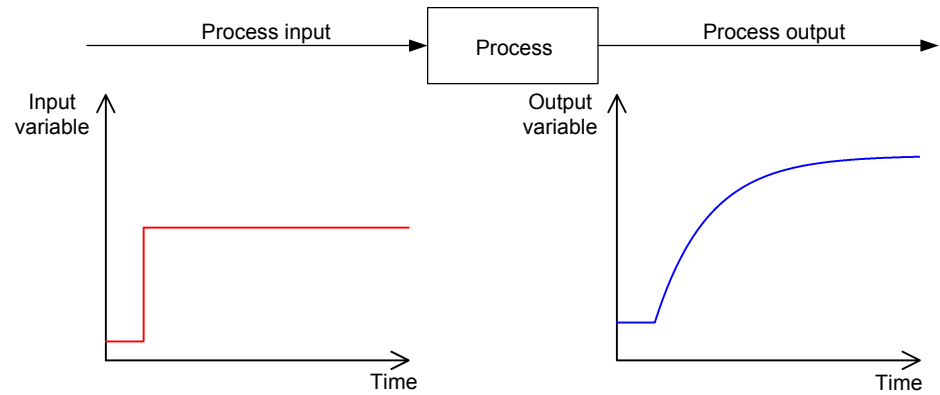


Figure 5-3. Classifying a process.

There are two main classes of processes: **self-regulating** processes and **non-self-regulating** processes. In a self-regulating process, if the input variable changes, the output variable stabilizes to a new value after a certain period of time. Unlike self-regulating processes, non-self-regulating processes do not stabilize. If the input variable changes, the output variable increases (or decreases) linearly or even exponentially without stabilizing. For the moment let us concentrate our efforts on self-regulating processes since they are more common than non-self-regulating processes. Figure 5-4 compares the response curve of a self-regulating process to the response curve of a non-self-regulating process.

The pressure control in a boiler is an example of a non-self-regulating process. If too much heat is applied, the vapor may not exit fast enough and the pressure inside the boiler rises instead of reaching a steady state.

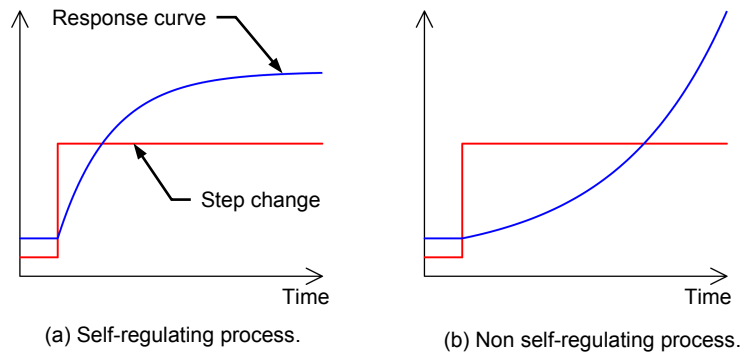


Figure 5-4. Response curve comparison.

**Single-capacitance processes**

We have already discussed resistance and capacitance elements in a process. Most of the time, a process is not purely resistive or capacitive. It is common to see a resistance element (e.g., a valve) and a capacitance element (e.g., a vessel) combined in a system. When a resistance element and a capacitive element are combined, the system is an **RC circuit**. In many aspects, the behavior of such an RC circuit is analogous to the behavior of an electric RC circuit made of a resistor and a capacitor.

An RC circuit that has one resistance element and one capacitance element is called a **single-capacitance process**. Single-capacitance processes are self-regulating processes because they tend to stabilize after a step change in the input variable. Single-capacitance processes are also called processes with **first-order response** because their response curve is the solution to the first-order differential equation that represents the process. Figure 5-5 shows a single-capacitance process that consists of a vessel with a constant input flow and an output flow that is a function of the opening of a valve. The vessel is the capacitance element since it can accumulate water and the valve is the resistive element. Thus, the input variable of the system is the input flow and the output variable is the level of water in the vessel. The input variable (i.e., the input flow rate) is identified as  $m$  and the output variable (i.e., the level) is identified as  $c$  because, in a process control system, the input variable is called the manipulated variable and the output variable is called the controlled variable.

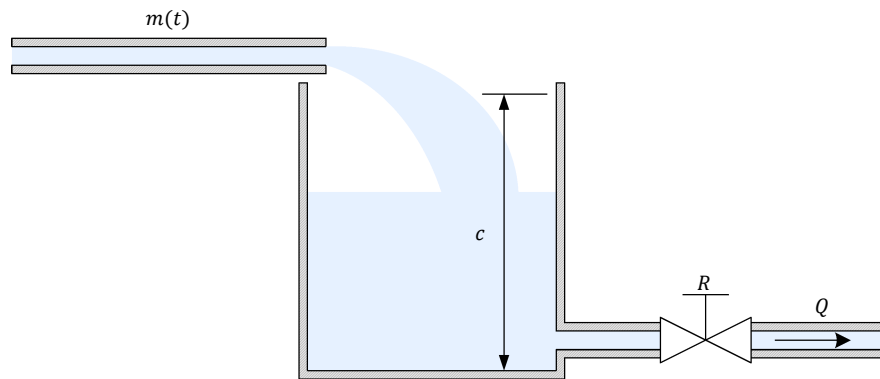


Figure 5-5. Single-capacitance level process.

Figure 5-6 shows the typical shape of the response curve of a single-capacitance process such as the level process presented above. The easiest way to recognize a single-capacitance process is to look at the graph of the output variable as a function of time and determine if the curve has a similar shape.

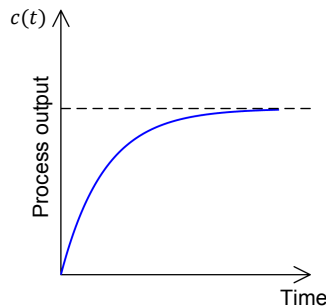


Figure 5-6. Response curve of a single-capacitance process.



### The mathematics behind single-capacitance processes

This section mathematically describes the single-capacitance process shown in Figure 5-5. Although this section is not necessary for understanding single-capacitance processes, it may help those of you who are familiar with differential equations. Moreover, the information in this section proves useful to those who wish to study advanced process control.

The **differential equation** modeling single-capacitance processes is:

$$\tau \frac{d}{dt} c(t) + c(t) = Km(t)$$

where  $\tau$  is the time constant of the process

$c(t)$  is the output of the process

$K$  is the gain (a constant)

$m(t)$  is the input of the process

This equation is a linear first-order differential equation. The differential equation is of the first order because the highest derivative in the equation is of the first order.

For a vessel that is filling, where the input flow is  $m(t) = M_0$  for  $t > 0$  and  $m(t) = 0$  for  $t < 0$ , the solution to the differential equation modeling single-capacitance processes is:

$$c(t) = KM_0(1 - e^{-t/\tau})$$

From this solution we can see why the curve shown in Figure 5-6 has the illustrated shape. Indeed, the solution to the differential equation modeling a single-capacitance process is an exponential function.

The electrical equivalent of the level process presented above is the RC circuit shown in Figure 5-7. Like its level process equivalent, this RC circuit has one capacitance element and one resistive element, a capacitor and a resistor respectively.

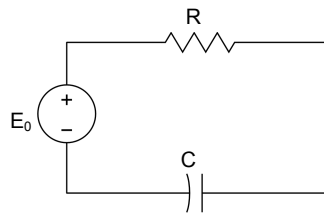


Figure 5-7. Electrical RC circuit.

Figure 5-8a shows the curve of the voltage across the capacitor as a function of time. This curve is similar to the response curve of the level process discussed above. Figure 5-8b shows the curve of the current in the RC circuit as a function of time. This type of curve is also typical of a single-capacitance process. In fact, both curves are exponential curves; more precisely, they both exhibit an exponential decay behavior because their rate of change is decreasing with time. The curve shown in Figure 5-8a differs from the second on the position of the asymptote, which is its horizontal limit, and by a constant.

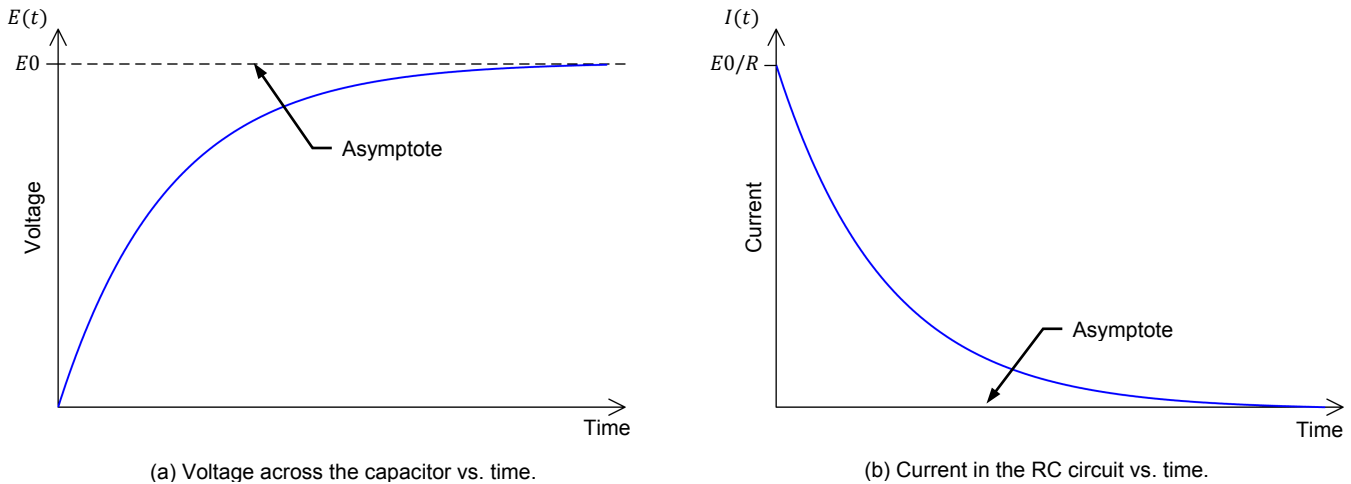


Figure 5-8. Response curves of a RC circuit.

### The mathematics behind electrical RC circuits

The current and voltage in the RC circuit shown in Figure 5-7 can also be modeled using first-order differential equations. The table below gives the differential equation for the voltage across the capacitor and for the current in the circuit. It also gives the solution to these differential equations.

	Voltage Across the Capacitor	Current in the Circuit
<b>Differential Equation</b>	$RC \frac{dE}{dt} + E = E_0$	$R \frac{dI}{dt} + \frac{1}{C} I = 0$
<b>Solution</b>	$E(t) = E_0(1 - e^{-t/(RC)})$	$I(t) = \frac{E_0}{R} e^{-t/(RC)}$

Looking at both solutions, it is clear why the curves shown in Figure 5-8 differ in shape. The solution for the voltage across the capacitor as a function of time has an extra constant  $E_0$  and the exponential function is subtracted from this constant.

If you compare the solution in the table above to the solution of the differential equation modeling single-capacitance processes, you can see that the exponents of these equations are alike. For the level process equation, the time constant is equal to the resistance of the process multiplied by the capacitance (i.e.,  $\tau = RC$ ). Similarly, the  $RC$  term in the solution of the differential equation of the RC circuit is the capacitive time constant of the circuit. Thus, for both systems,  $\tau = RC$ .

The time constant is an important characteristic of dynamical processes; it is discussed in detail in the following section.

### Process characteristics

This section describes the dynamic characteristics of a single-capacitance process. Figure 5-9 shows a first-order response curve for a single-capacitance process. This figure also shows, above the response curve, the step change in the manipulated variable.

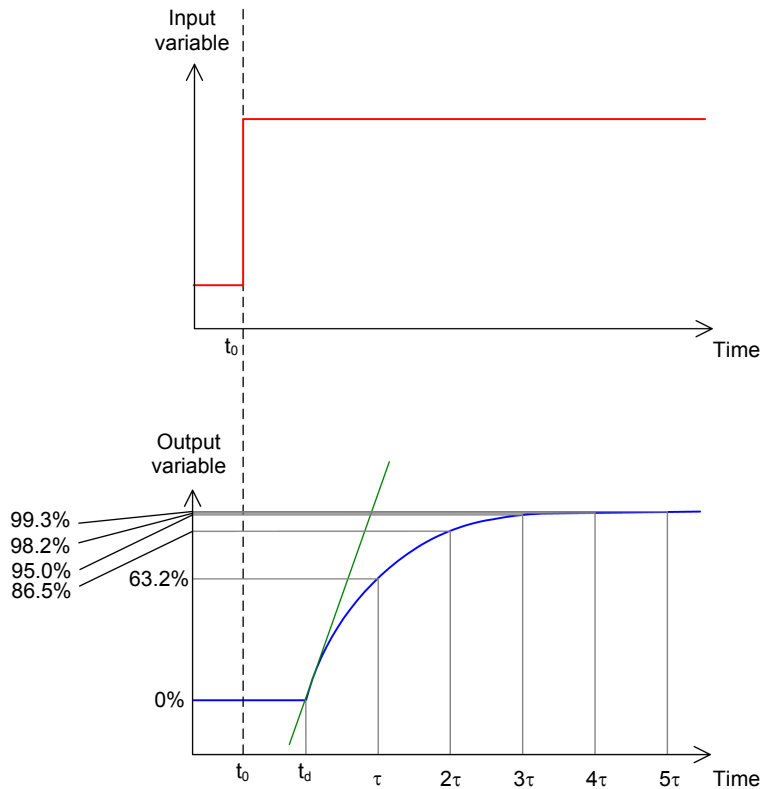


Figure 5-9. Response curve of a single-capacitance process.

**Dead time**

The **dead time**,  $t_d$ , of a process is the time period elapsing between the step change of the input variable (at  $t_0$ ) and the first variation of the output variable. During the dead time, nothing changes in the output signal. The time it takes to transport a solid, a liquid, or a gas to the process causes a dead time. Some mechanical or electronic parts also take time to react; this delay is also part of the dead time of the process. The dead time is also influenced by the time the process takes to react (**process lag**), the time the sensor(s) take(s) to react, and the time the controller takes to react (**control lag**). Figure 5-10 shows an example of process lag. In this example, a candle is heating a metal bar and the heat takes time to reach the hand holding the bar. The time it takes for the heat to reach the hand is the process lag.

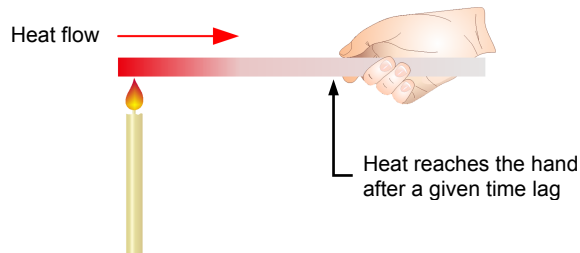


Figure 5-10. Process lag.

**Time constant**

The response curve of a single-capacitance process, shown in Figure 5-9, has a slope that changes with time. The slope of the curve is the rate at which the output variable changes with time. The slope of the response curve is at its maximum when the curve starts to rise. The **time constant**,  $\tau$ , is the time it would have taken for the output variable to reach its final value if it had kept its initial rate of change. For a process with a first-order response, the time constant corresponds to the time it takes for the output variable to reach 63.2% of the total increase or decrease that follows the step change in the input variable minus the dead time, if any. The time constant depends on the time delay that resistance(s) and capacitance(s) cause. Figure 5-11 shows the relationship between the time constant and the maximum slope of a first-order response curve.

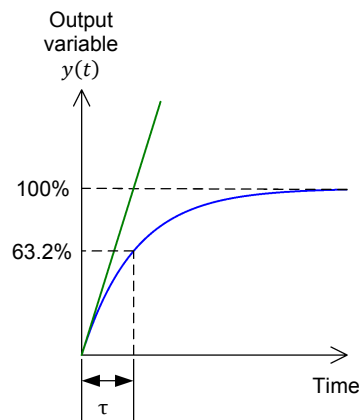


Figure 5-11. Time constant.

**The mathematics behind the time constant**

Single-capacitance processes have a response curve that follows the relationship below:

$$y(t) = y_0(1 - e^{-t/\tau})$$

where  $\tau$  is the time constant of the process  
 $y(t)$  is the output of the process  
 $y_0$  is maximum value of the output variable  
 $t$  is the time

Since this equation is an exponential function, it reaches its maximum at the initial time  $t = 0$ . The slope of this curve is the first derivative of the function:

$$\frac{dy}{dt} = \frac{y_0}{\tau} e^{-t/\tau}$$

Thus, the slope at  $t = 0$  is  $\frac{y_0}{\tau}$ . The equation of a line with this slope is:

$$z = \frac{y_0}{\tau} t$$

This line reaches the maximum value of the exponential curve  $y_0$  when the time is equal to the time constant  $\tau$  (i.e.,  $z = y_0$  at  $t = \tau$ ).

At  $t = \tau$  the equation for a single-capacitance process becomes:

$$y(\tau) = y_0(1 - e^{-\tau/\tau})$$

$$y(\tau) = y_0(1 - e^{-1})$$

$$y(\tau) = y_0(1 - 0.368) = 0.632y_0$$

Thus, the time it takes for the process to reach 63.2% of its maximum value is the time constant of the process. Using this method, it is easy to deduce that the process reaches 86.5% of its maximum value at  $t = 2\tau$ , 95.0% of its maximum value at  $t = 3\tau$ , 98.2% of its maximum value at  $t = 4\tau$ , and 99.3% of its maximum value at  $t = 5\tau$ .

**Process gain**

The **process gain**,  $K_p$ , is the ratio of the output variable change to the change in the input variable. The output variable and input variable are expressed as a percentage of span; therefore, the process gain is dimensionless.

$$K_p = \frac{\Delta output}{\Delta input} \quad (5-1)$$

Figure 5-12 illustrates this definition using the graph of the step change in the input variable and the response curve of the process to this step change.

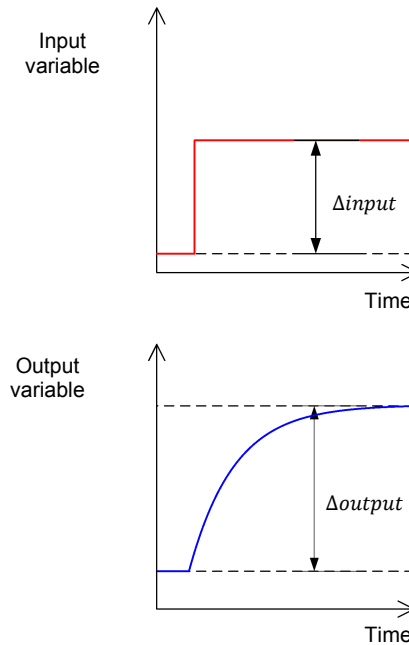


Figure 5-12. Process gain.

*Other characteristics*

Steady state	The output reaches 99.3% of its maximum value after five time constants. At this point, you can consider that the process is at <b>steady state</b> .
Response time	The <b>response time</b> is the time it takes for the process output to reach a predetermined percentage of the steady-state value. In Figure 5-9 the response time to reach 95% is about $t_d + 3\tau$ .
Rise time	The <b>rise time</b> is the time it takes for the process output to change from a small to a large percentage of the steady-state value. For example, the rise time of a process can be the time it takes for the process output to go from 5% to 95% of the steady-state value.
Settling time	The <b>settling time</b> is the time it takes for the process output to stabilize within a predetermined percentage of the steady-state value. This percentage can be, for example, 2%. In the example shown in Figure 5-9, the process output enters and remains within 2% of the steady-state value after a settling time of about $t_d + 4\tau$ .

## Determining the Dynamic Characteristics of a Process

**EXERCISE OBJECTIVE** In this exercise, you will determine the dynamic characteristics of a process.

**DISCUSSION OUTLINE** The Discussion of this exercise covers the following points:

- Open-loop method
- How to obtain an open-loop response curve
- Preliminary analysis of the open-loop response curve
- Analyzing the response curve

### DISCUSSION

#### Open-loop method

Ultimately, the purpose of determining the dynamic characteristics of a process is to obtain enough information on the process to be able to tune the controller for efficient process control. There are two different approaches for tuning a controller. The closed-loop approach uses the automatic mode of the controller, while the open-loop approach uses the manual mode of the controller. In this exercise, you will use open-loop approaches to tune your controller. This type of approach provides a quick estimate of the controller tuning settings.

The controller is set to manual mode and is only used to create the step change in the input variable that triggers a process response (open-loop response curve). This method requires a self-regulating process. For non-self-regulating processes, a different method must be used to tune the controller.

An analysis of the open-loop response curve enables the determination of the following process characteristics:

- Dead time,  $t_d$
- Time constant,  $\tau$
- Process gain,  $K_p$
- Order of response (first order or  $n^{\text{th}}$  order)

### **How to obtain an open-loop response curve**

To obtain the open-loop response curve of a process, you must have a system with the following:

- Primary/secondary element that is properly installed and configured
- Recorder with at least two channels
- Controller
- Calibrator
- Final control element

To record both the response curve and the step change with the recorder, both the calibrator and the output of the secondary element must be connected to a channel of the recorder.

If available, a digital recorder allowing export of the recorded data to spreadsheet software should be used. Using spreadsheet software to analyze the response curve gives more precise results than a graphical analysis alone.

Both channels of the recorder should be plotted in units of 0% to 100% of the measured variable range. The calculation to determine the tuning parameters of the controller is easier if you set the units for the horizontal axis to minutes or fractions of minutes. This can be done directly on the recorder or afterward in the spreadsheet software.

### ***Steps to obtain the response curve***

Below are the general steps to obtain the response curve:

1. Make sure your controller is in manual mode.
2. Start your system and set the calibrator output to a given value (e.g., 60%).
3. Wait for the system to stabilize and start recording the calibrator output and the measured variable on the recorder.
4. Create a step change in the manipulated variable by suddenly changing the calibrator output.
5. Wait for the system to be at steady state.
6. Stop your system and prepare your data for analysis.



## Preliminary analysis of the open-loop response curve

### Determine the process order

Remember that the analysis of the response curve should provide four essential characteristics of the process. One of these characteristics is the order of the process. Before selecting the method for analyzing the response curve, you can determine if your process is a single-capacitance process (first-order) or a multiple capacitance process ( $n^{\text{th}}$  order) just by looking at the shape of the response curve. Figure 5-13 shows the difference between the response curve of a single-capacitance process and a multiple-capacitance process. This figure also shows the tangent to the curve at the point where the slope is maximum. The latter has a response curve with an exaggerated “S” shape. On this curve, the point at which the slope is maximum is in the “S” instead of at the beginning of the curve. This point is the inflection point of the curve, which is the point where the curvature changes sign.

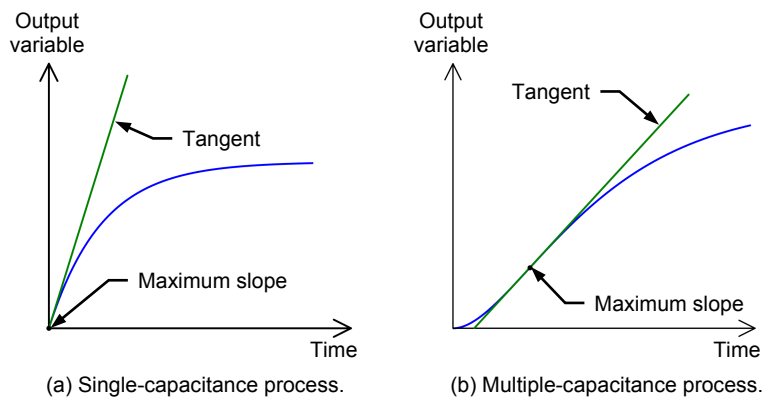


Figure 5-13. Determination of the process order.

Once you have determined if your process is a single-capacitance process or a multiple capacitance process and you have calculated the process gain, you must prepare the response curve for further analysis using one of the three suggested methods. This allows you to determine the dead time and the time constant of the process.

### Determine the process gain

As shown in Equation (5-2), you can easily determine the process gain by dividing the percentage of change in the process variable after the step change ( $\Delta output$ ) by the height of the step change in percent ( $\Delta input$ ).

$$K_p = \frac{\Delta output}{\Delta input} \quad (5-2)$$

Figure 5-14 shows how you can determine the process gain using the response curve. The gain of the process with the response curve shown is:

$$K_p = \frac{\Delta output}{\Delta input} = \frac{80\%}{30\%} = 2.67$$

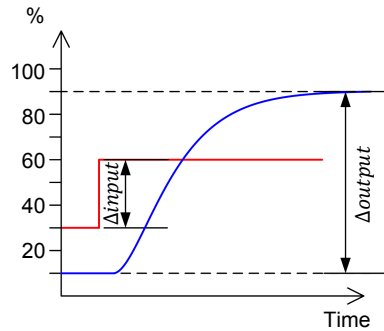


Figure 5-14. Calculating the process gain.

**Prepare the response curve for analysis**

A little bit of preparation is required before you can analyze the response curve using one of the methods below. Figure 5-15 shows a typical response curve before preparation for analysis. On this graph, the response curve starts before the step change and it does not occupy the vertical scale from 0% to 100%.

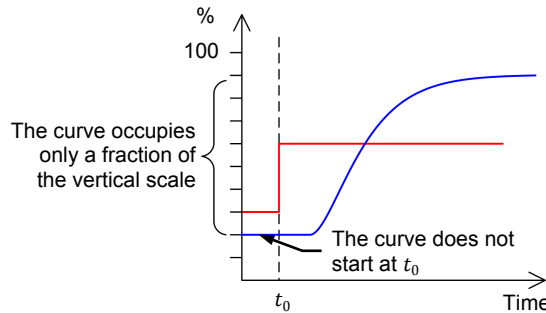


Figure 5-15. Response curve before preparation for analysis.

To allow an easier analysis, it is convenient to plot the data on a new graph with the horizontal time scale starting at the moment the step change was created. You must also set the vertical scale so that the curve starts at 0% and reaches 100% when it is at steady state. This way, the curve occupies 100% of the vertical scale of the graph.

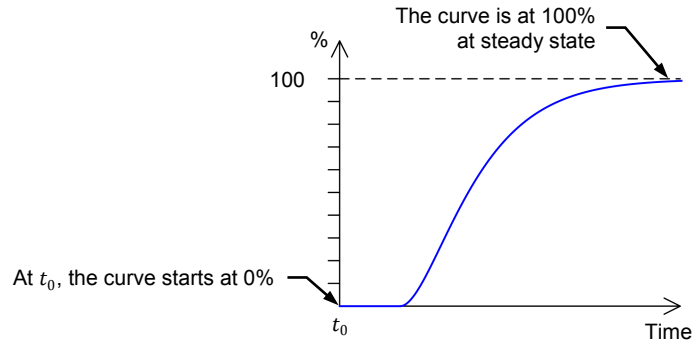


Figure 5-16. Response curve ready for analysis.

### Analyzing the response curve

The approach for determining the gain and the process order from the open loop response curve is straightforward and does not vary from one method to another. However, there are different methods for determining the time constant and the dead time of a process from the open-loop response curve.

This section provides three methods for analyzing the response curve. Although these methods give slightly different results, they are all acceptable and suitable for most processes. The first one is a **graphical method** suggested by Ziegler and Nichols as part of their well known method for tuning PID controllers. This graphical method requires a fine and careful analysis of the graph and may give only middling results. The two other methods give more consistent results since they rely on the analysis of the data rather than the graph.

#### *Graphical method (Ziegler-Nichols)*

This method of analysis requires a paper copy of the response curve ready for analysis. On the response curve you must determine the point where the curve is the steepest. For a first-order response curve, this point is right where the curve starts to rise as Figure 5-17a shows. For an  $n^{\text{th}}$  order response curve, the maximum slope is at the inflection point where the curvature of the response curve changes from concave to convex, as Figure 5-17b shows. Once you have determined the point where the slope is at its maximum, draw a tangent line passing through this point.

On the graph, the point where the line intercepts the abscissa is the dead time. For a first-order curve, the dead time is the time elapsed before the process variable starts to rise. For an  $n^{\text{th}}$  order curve, the process variable begins to change before the dead time ends. The time constant of the process is the time it takes for the process variable to reach 63.2% of its maximum value. For a first-order process, the time constant also corresponds to the point where the line you have drawn intercepts the 100% asymptote.

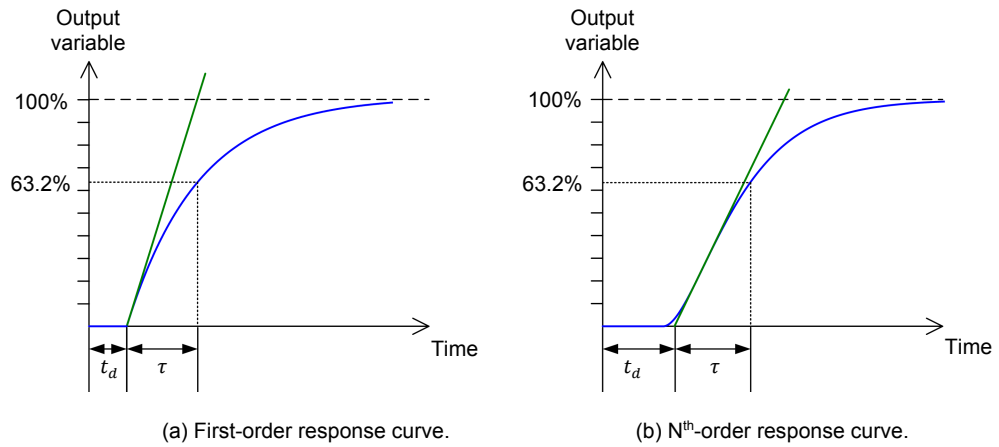


Figure 5-17. Graphical method.

**2%–63.2% method**

For  $n^{\text{th}}$  order response curves, it is sometimes difficult to determine the position of the inflection point. To eliminate error due to the interpretation of the curve, you can use this second method. With this method, the dead time corresponds to the time it takes for the process variable to reach 2% of the total change. The time constant is the time it takes for the process variable to increase from 2% to 63.2%. Figure 5-18 illustrates this method.

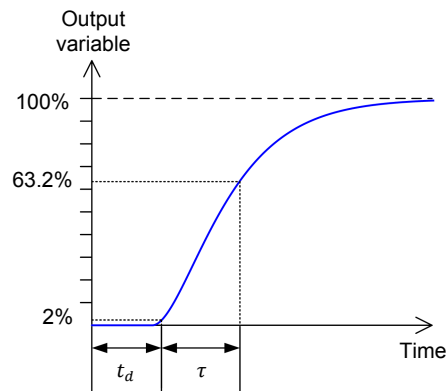


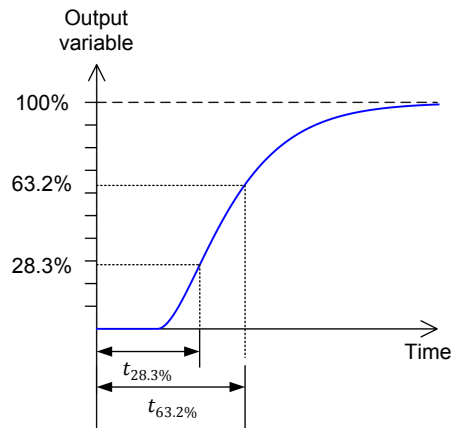
Figure 5-18. 2%–63.2% method.

**28.3%–63.2% method**

The third method consists of evaluating the time it takes for the process variable to reach 28.3% and 63.2% of the 100% span. Once you have these two values, use Equation (5-3) to calculate the time constant and Equation (5-4) to calculate the dead time. Figure 5-19 illustrates this method.

$$\tau = 1.5(t_{63.2\%} - t_{28.3\%}) \quad (5-3)$$

$$t_d = t_{63.2\%} - \tau \quad (5-4)$$



**Figure 5-19. 28.3%–63.2% method.**

**PROCEDURE OUTLINE**

The Procedure is divided into the following sections:

- Set up and connections
- Transmitter calibration
- Characterization of the pressure process
- End of the exercise

**PROCEDURE****Set up and connections**

*In this process, the controlled variable will be the pressure of the air confined within the column. The manipulated variable will be the flow of water into the column. The final control element will be the pump drive.*

1. Set up the pressure process shown in Figure 5-20.
  - Mount the rotameter and the column on the expanding work surface.
  - Connect the pump outlet to the port of the column that is attached to a pipe that extends down into the column.
  - Block the unused hose ports of the column using the provided plugs.
  - Firmly tighten the top cap.

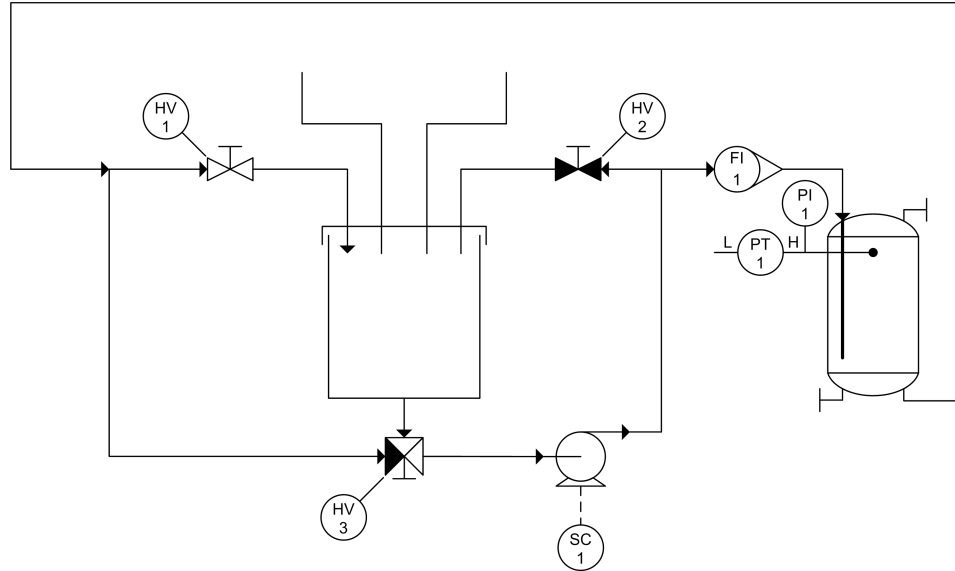


Figure 5-20. Characterization of a pressure process set up.

**Note for the instructor:** Alternately, the final control element can be the optional control valve.

2. Power up the DP transmitter.
3. Make sure the reservoir of the pumping unit is filled with about 12 liters (3.2 gallons) of water. Make sure the baffle plate is properly installed at the bottom of the reservoir.
4. On the pumping unit, adjust valves HV1 to HV3 as follows:
  - Open HV1 completely.
  - Close HV2 completely.
  - Set HV3 for directing the full reservoir flow to the pump inlet.
5. Turn on the pumping unit.

### Transmitter calibration

*In steps 6 through 11, you will be adjusting the **ZERO** and **SPAN** adjustments of the DP transmitter so that its output current varies between 4 mA and 20 mA when the pump speed is varied between 0% and 100%.*

6. Connect a multimeter to the 4-20 mA output of the DP transmitter.

7. Make the following settings on the DP transmitter:
  - **ZERO** adjustment knob: **MAX**.
  - **SPAN** adjustment knob: **MAX**.
  - **LOW PASS FILTER** switch: **O (OFF)**
8. With the pump speed at 0%, the air pressure within the column is minimum. Turn the **ZERO** adjustment knob of the DP transmitter counterclockwise and stop turning it as soon as the multimeter reads 4.00 mA.
9. Make the pump run at 100%. Observe that the water level rises in the column, thereby compressing the air confined within the column and causing the air pressure to increase as indicated by pressure gauge PI1. Wait until the water level has stabilized in the column.



*The air pressure in the column is now maximum. It is equal to the pressure of the water in the column and, therefore, to the pressure required to counteract the resistance to flow caused by the components downstream of the column.*

10. Adjust the **SPAN** knob of the DP transmitter until the multimeter reads 20.0 mA.



*If the top cap of the column is not tightened firmly, pressurized air escapes and the water level does not stabilize. If this happens, stop the pump and remove the top cap to empty the column into the reservoir. Once the column is empty, tighten the top cap with more force and resume the procedure from step 8.*

11. Due to interaction between the **ZERO** and **SPAN** adjustments, repeat steps 8 through 11 until the DP transmitter output actually varies between 4.00 mA and 20.0 mA when the controller output is varied between 0% and 100%.

### Characterization of the pressure process

12. Have the following signals plotted on a trend recorder:
  - Controlled variable,  $c(t)$ , the DP transmitter output
  - Manipulated variable,  $m(t)$ , the controller output

#### LVProSim

Connect the computer running LVProSim to the pump and DP transmitter via the I/O interface.

To control the pump speed using LVProSim, connect the variable-speed drive to output 1 of the I/O interface. With this configuration, you can modify the pump speed by changing the output signal manually in the appropriate PID controller section of LVProSim.

Follow the steps below to plot the transmitter output signal on the trend recorder of the software (proceed similarly to plot the controller output).

Press the Set Channels icon in the LVProSim menu bar and, in the Set Channels window, select the channel number corresponding to the input on the I/O interface to which the DP transmitter is connected. Then:

- Enter the name you want to give to the channel in the Label text box.
- Select Percentage as the type of measured variable.
- Select % as the measurement unit.
- Enter 0°% in the Minimum value field and 100°% in the Maximum value field. These values correspond to 4 mA and 20 mA signals, respectively.

From the Settings menu, change the sampling interval to 200 ms. Add the channel to the curves list at the bottom of the trend recorder and press the play button in the menu bar to start recording data. To add a channel to the curves list, select the label from the drop-down list that corresponds to the channel you want to add and press ADD. Refer to Appendix B for details on how to use the trend recorder.

**13.** Decrease the pump speed to 65%.

**14.** In the space provided below, record the output of the DP transmitter once it has stabilized on the trend recorder.

The output should be about 40.6%.

### LVProSim

Data recorded with LVProSim can be exported to a csv file using the export button in the menu bar. The export function saves the data file to your browser downloads folder. This file can be imported later into a spreadsheet program for accurate measurement of the process characteristics.

**15.** Suddenly increase the pump speed from 65% to 85%. In the space provided below, record the output of the DP transmitter once it has stabilized on the trend recorder.

The output should be about 73.6%.

**16.** Stop (pause) the trend recorder.

**17.** Stop the pump and turn off the pumping unit.



**Curves analysis**

18. Determine the total change in DP transmitter output that followed the step change in controller output. Express your answer as a percentage of the DP transmitter output span

The change corresponds to a percentage of output span of about 33.0%.

19. Calculate the process gain  $K_p$  using Equation (5-2) and record it in Table 5-1.

**Table 5-1. Characteristics of the pressure process.**

Characteristic	Value
Process gain, $K_p$	
Time constant, $\tau$	
Dead time, $t_d$	

**Characteristics of the pressure process.**

Characteristic	Value
Process gain, $K_p$	$\cong 1.65$
Time constant, $\tau$	$\cong 4.5$ seconds
Dead time, $t_d$	$\leq 0.25$ second

20. Determine the time constant of the process by measuring, on the trend recorder, the time it took for the controlled variable to reach approximately 63.2% of the total change that followed the step change in manipulated variable. Record the time constant in Table 5-1.

21. How would the dead time be affected if the DP transmitter had a slower response time?

The dead time would be longer.

22. If possible, determine the dead time of the process by measuring, on the trend recorder, the time difference between when the manipulated variable was changed suddenly and when the controlled variable first started to change. Record the dead time in Table 5-1.

23. Determine whether the pressure process is of the first- or second-order type. Explain.

The pressure process is of the first-order type, because the maximum slope of the response curve occurs immediately when the controlled variable starts to increase.

### End of the exercise

24. Disconnect the circuit. Return the components and hoses to their storage location.
25. Wipe off any water from the floor and the training system.

### CONCLUSION

In this exercise, you learned that a process is mainly characterized by three parameters, which are the process gain, the time constant, and the dead time. These characteristics can be determined from the response curve of the process to a sudden (step) change in manipulated variable.

### REVIEW QUESTIONS

1. What is the purpose of finding the dynamic characteristics of a process?

Finding the dynamic characteristics of a process allows you to tune the controller for efficient process control.

2. How does a process with a large gain react to a step change?

For a process with a large gain, the process variable (the output) varies a lot for a small variation of the manipulated variable (the input).

3. What is an inflection point for the response curve of an  $n^{\text{th}}$  order process?

An inflection point is the point on the response curve where the curvature changes from concave to convex. At this point, the curve slope is maximum.

4. Which of the three methods presented for analyzing a response curve is most subject to interpretation?

The graphical method of analyzing a response curve is most subject to interpretation.

5. Which process characteristics does a careful analysis of an open-loop response curve allow you to determine?

The dead time, the time constant, the process gain, and order of the response curve can be determined through a careful analysis of an open-loop response curve.

## Unit Test

1. A process is a
- dynamical system.
  - system that evolves with time.
  - sequence of actions.
  - All of the above are correct.

d

2. Which element can execute the decision task in a process control system?
- Primary element
  - Pump
  - PLC
  - None of the above is correct.

c

3. The pressure loss that pipes cause in a process control system are a type of
- resistance.
  - capacitance.
  - inertia.
  - inductance.

a

4. A single-capacitance process is a system that has
- an element of resistance and an element of inertia.
  - an element of resistance and an element of capacitance.
  - an element of capacitance and an element of inertia.
  - None of the above is correct.

b

5. The response curve of a single-capacitance process has a
- parabolic shape.
  - exponential shape.
  - hyperbolic shape.
  - symmetric shape.

b

6. The response curve of an  $n^{\text{th}}$  order process has a
- a. C shape.
  - b. J shape.
  - c. U shape.
  - d. S shape.

d

7. A single-capacitance process has a
- a. first-order response curve.
  - b. second-order response curve.
  - c.  $n^{\text{th}}$ -order response curve.
  - d.  $h$ -order response curve.

a

8. A non-self-regulating process is a process
- a. with a substance that helps regulation.
  - b. that stabilizes slowly.
  - c. that does not stabilize.
  - d. None of the above is correct.

c

9. For a given process, it takes 1 minute 46 seconds for the process variable to go from 28.3% to 63.2% of the span after a step change. What is the time constant for this process?
- a. The time constant for this process cannot be calculated from this information.
  - b. 159 seconds
  - c. 1 minute 59 seconds
  - d. 106 seconds

b

10. The dead time of a process is 6 minutes and the time constant is 48 minutes. When does the process variable reach 63.2% of the span?
- a. After 48 minutes
  - b. After 42 minutes
  - c. After 54 minutes
  - d. Never

c

# Bibliography

Bird, R. Byron, Stewart, W.E, and Lightfoot, E.N. *Transport Phenomena*, New York: John Wiley & Sons, 1960, ISBN 0-471-07392-X.

Chau, P.C. *Process Control: A First Course with MATLAB*, Cambridge University Press, 2002, ISBN 0-521-00255-9.

Coughanowr, D.R. *Process Systems Analysis and Control*, Second Edition, New York: McGraw-Hill Inc., 1991, ISBN 0-07-013212-7.

Liptak, B.G. *Instrument Engineers' Handbook: Process Control*, Third Edition, Pennsylvania: Chilton Book Company, 1995, ISBN 0-8019-8542-1.

Liptak, B.G. *Instrument Engineers' Handbook: Process Measurement and Analysis*, Third Edition, Pennsylvania: Chilton Book Company, 1995, ISBN 0-8019-8197-2.

Luyben, M.L., and Luyben, W. L. *Essentials of Process Control*, New York: McGraw-Hill Inc., 1997, ISBN 0-07-039172-6.

Luyben, W.L. *Process Modeling, Simulation and Control for Chemical Engineers*, Second Edition, New York: McGraw-Hill Inc., 1990, ISBN 0-07-100793-8.

McMillan, G.K. and Cameron, R.A. *Advanced pH Measurement and Control*, Third Edition, NC: ISA, 2005, ISBN 0-07-100793-8.

McMillan, G.K. *Good Tuning: A Pocket Guide*, ISA - The Instrumentation, Systems, and Automation Society, 2000, ISBN 1-55617-726-7.

McMillan, G.K. *Process/Industrial Instruments and Controls Handbook*, Fifth Edition, New York: McGraw-Hill Inc., 1999, ISBN 0-07-012582-1.

Munson, B.R., Young, D.F., and Okiishi, T.H. *Fundamentals of Fluid Mechanics*, Fourth Edition, John Wiley & Sons Inc., 2002, ISBN 0-471-44250-X.

Perry, R.H. and Green, D. *Perry's Chemical Engineers' Handbook*, Sixth Edition, New York: McGraw-Hill Inc., 1984, ISBN 0-07-049479-7.

Raman, R. *Chemical Process Computation*, New York: Elsevier applied science ltd, 1985, ISBN 0-85334-341-1.

Ranade, V.V. *Computational Flow Modeling for Chemical Reactor Engineering*, California: Academic Press, 2002, ISBN 0-12-576960-1.

Shinskey, G.F. *Process Control Systems*, Third Edition, New York: McGraw-Hill Inc., 1988, ISBN 978-0070569034.

Smith, Carlos A. *Automated Continuous Process Control*, New York: John Wiley & Sons, Inc., 2002, ISBN 0-471-21578-3.

Soares, C. *Process Engineering Equipment Handbook*, McGraw-Hill Inc., 2002, ISBN 0-07-059614-X.

Weast, R.C. *CRC Handbook of Chemistry and Physics*, 1<sup>st</sup> Student Edition, Florida: CRC Press, 1988, ISBN 0-4893-0740-6.