Mech 366
Modeling of Mechatronic Systems

Lab #2
Introduction to Data Acquisition and LabVIEW
Part 2. Process Control Using LabVIEW

LEARNING OBJECTIVES

- Use LabVIEW G programming in data acquisition and process control.
- Introduce and compare two control strategies: ON/OFF and proportional control.
- Implement the two control algorithms into a working LabVIEW virtual instrument.
- Apply the developed LabVIEW program in the control of the liquid level in a tank.
- Examine the time response of the system under the different control strategies.
- Examine the behavior of the two control strategies in response to disturbances in the system loads.
- Examine the behavior of the system to a step input.

BACKGROUND

Tank Level Control

Figure 1 shows the two-tank system that continuously supplies two different processes with two different flow rates. It is required to maintain the level in Tank B by controlling the flow through the proportional control valve.

In this section, you are asked to augment the supplied Tank Level Control VI with the necessary instructions that allow ON/OFF and proportional control of the level in a tank. The front panel and block diagram of the Tank Level Control VI are shown in Figures 1, 2a, and 2b. Note that in the block diagram the True/False case structure corresponding to the selected controller is intentionally left blank for you to complete. The purpose of this VI is to perform the following functions:

To continuously acquire signals from pressure transducers placed in the base of the two liquid tanks.

- To convert the acquired readings into voltages.
- To convert the voltages into liquid heights.
- To allow the user to select either ON/OFF control or proportional control of level.
- To select an appropriate voltage (0 - 10 volts) to control the input flow through a proportional control valve according to the desired control strategy.
- To convert the voltage into integer counts.
- To send the selected control signal to the control valve.

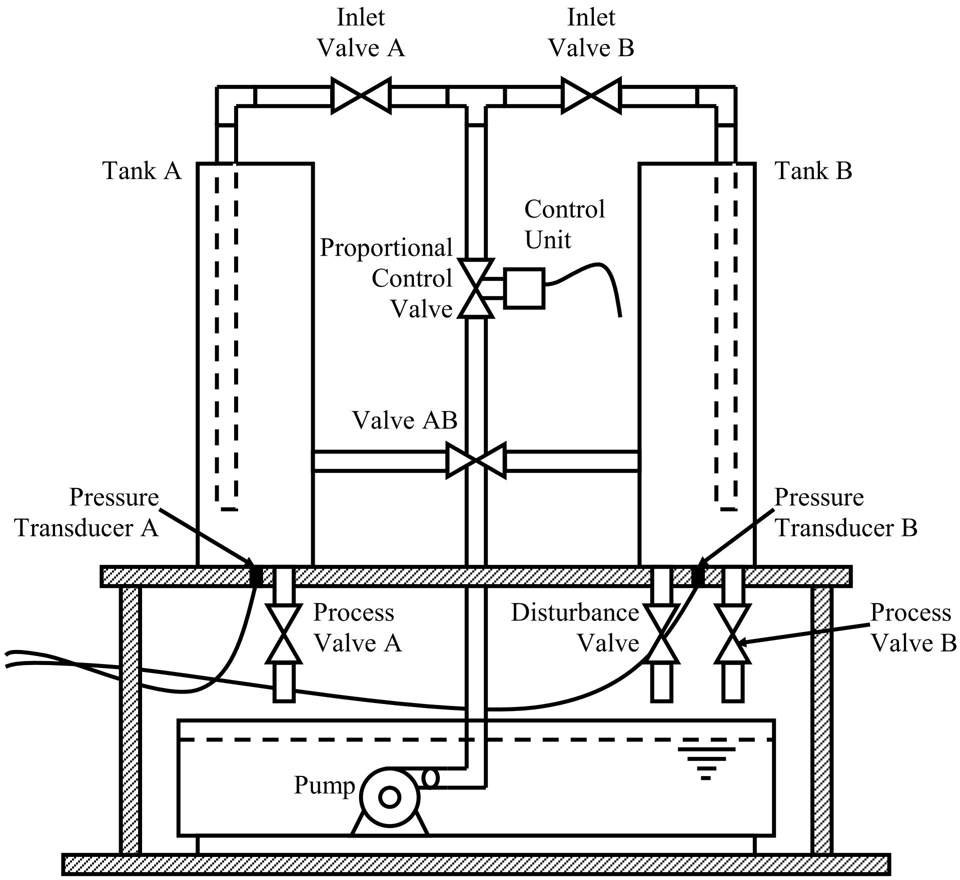


Figure 1. Schematic of the Tank Level Control Setup.

Description of the Front Panel

As shown in Figure 2, the front panel of the Tank Level Control VI consists of the following controls and indicators:

1. A control switch to shift between ON/OFF control and proportional control.
2. Two digital controls to set the high and low limits for the ON/OFF control.
3. Two digital controls to define the set value and gain for the proportional control.
4. A waveform chart to plot the acquired tank level as well as the high limit, the low limit and the set value.
5. Four digital indicators to show Tank A level, Tank B level, the voltage signal to the proportional control valve and the elapsed time.
6. A stop button

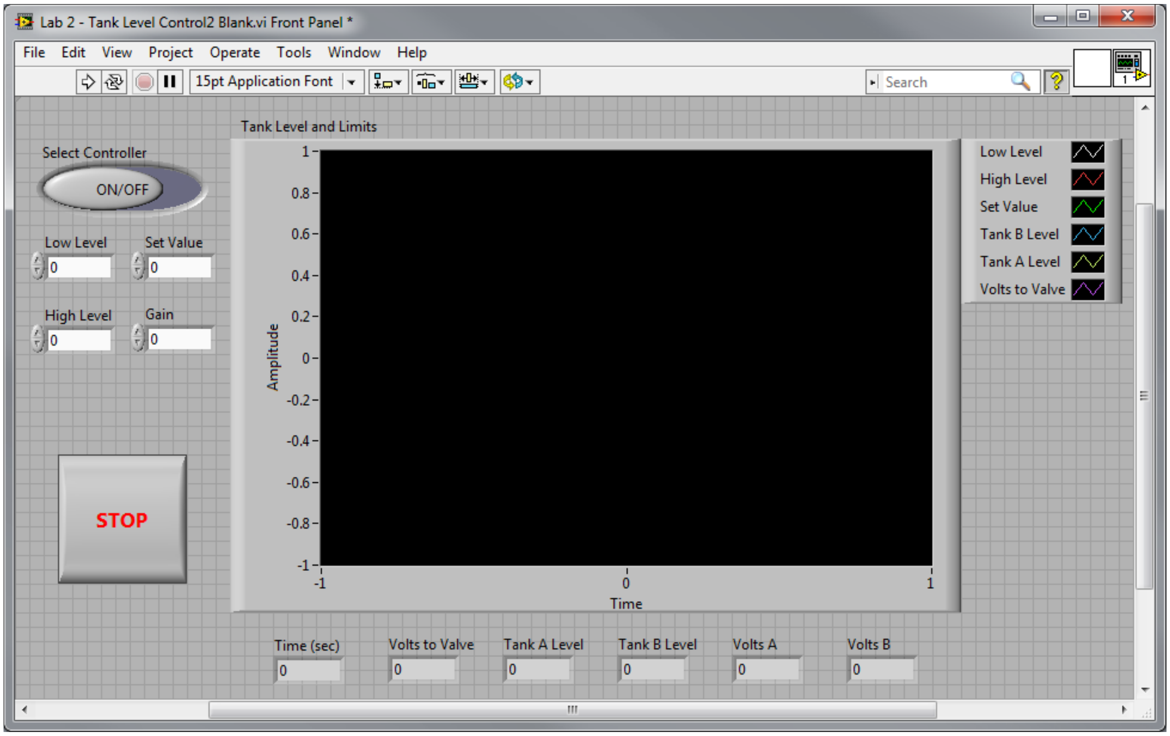


Figure 2. **Front Panel of the Tank Level Control VI.**

Description of the Block Diagram

A LabVIEW feature for While Loops, which is used in the block diagram of the *Tank Level Control.vi* shown in Figures 3a and 3b and which was not introduced in the previous *Tank Level Display.vi*, is the *Shift Register* function. Shift Registers transfer values from one iteration of a While Loop to the next. They are comprised of a pair of terminals directly opposite each other on the vertical sides of the While loop border. You can create a Shift Register by popping up on the left or right loop border and selecting *Add Shift Register* from the pop-up menu. The right terminal (the rectangle with the up arrow) stores the data wired to it at the end of the While loop iteration. The stored data from the previous iteration is shifted to the left terminal (the rectangle with the down arrow) at the beginning of the next iteration.

One more LabVIEW function, *Case Structures*, will be used in the *Tank Level Control.vi*. A Case Structure is a method of executing conditional instructions that is analogous to the common If…Then…Else statements in conventional text-based programming languages. You place the Case Structure on the block diagram by selecting it from the Structures subpalette of the Functions palette. The Case Structure has multiple subdiagrams of which only one subdiagram is visible at a time. Selection of the diagram identifier (True/False) shown at the top of the Case Structure border causes the corresponding subdiagram to execute. The Boolean diagram identifier must be wired to the question mark on the structure border. As with the While loop, you can wire a terminal from outside the case structure to a terminal within the structure. When you do this a small orange rectangular box will appear on the structure border.

Figure 3a shows the block diagram with the ON/OFF controller case selected while Figure 3b shows the block diagram with the proportional controller case. In both cases, you must provide the necessary instructions within the Case Structure box to implement the two control algorithms. The block diagram consists of the following functions:

1. Terminals corresponding to the control switch, digital controls, digital indicators, waveform chart and stop button on the front panel.
2. The subVI *Get Single Scan.vi* to acquire the reading from the pressure transducer.
3. Conversion factors to transform the acquired volts into liquid level units. Use the values you obtained from the Tank Level Display calibration experiment.
4. A Case Structure that can allow for two different sets of instructions to be executed according to the selected control algorithm. The case structure has all the necessary variables, which need to be used within, wired to its left border. The output from the right border of the case structure should be the voltage signal to be send to the flow control valve. *(This is "TRUE=Proportional Control" and "FALSE=ON/OFF Control")*
5. Conversion factors to transform the voltage into integer counts.
6. The subVI *A0 One Point.vi* to send the signal to the valve.
7. A while loop to continuously repeat the data acquisition and control process. The while loop has Shift Registers attached to its border to allow for the previous value of the control voltage signal to be stored and made available for use in the next iteration of the while loop.
8. A timing function to control the time between two successive While loop iterations and to calculate the elapsed time.
9. A True/False case structure that sends a 0 volts signal to the valve to terminate the control process once the stop button is hit.

PROCEDURE

****Use the same apparatus as your Lab1 experiment so you can use the same calibration factors from Lab1 in this experiment***

1. Open the VI *Tank Level Control.vi* under the C:\MECH 366 directory. This is a pre-built VI that is similar to your Lab1 but with a blank control section for you to fill in.
2. You are required to provide the necessary instructions within the Case Structure box to implement both the ON/OFF and proportional control algorithms as described in the next sections. You will also need to add the "High" and "Low" lines for ON/OFF control to the Case Structure. ***(See Appendix for a review of ON/OFF and Proportional Control)***
3. Insert the calibration factors in the block diagram of the VI.
4. Test your implemented control algorithms.
5. Save your work on a USB drive.

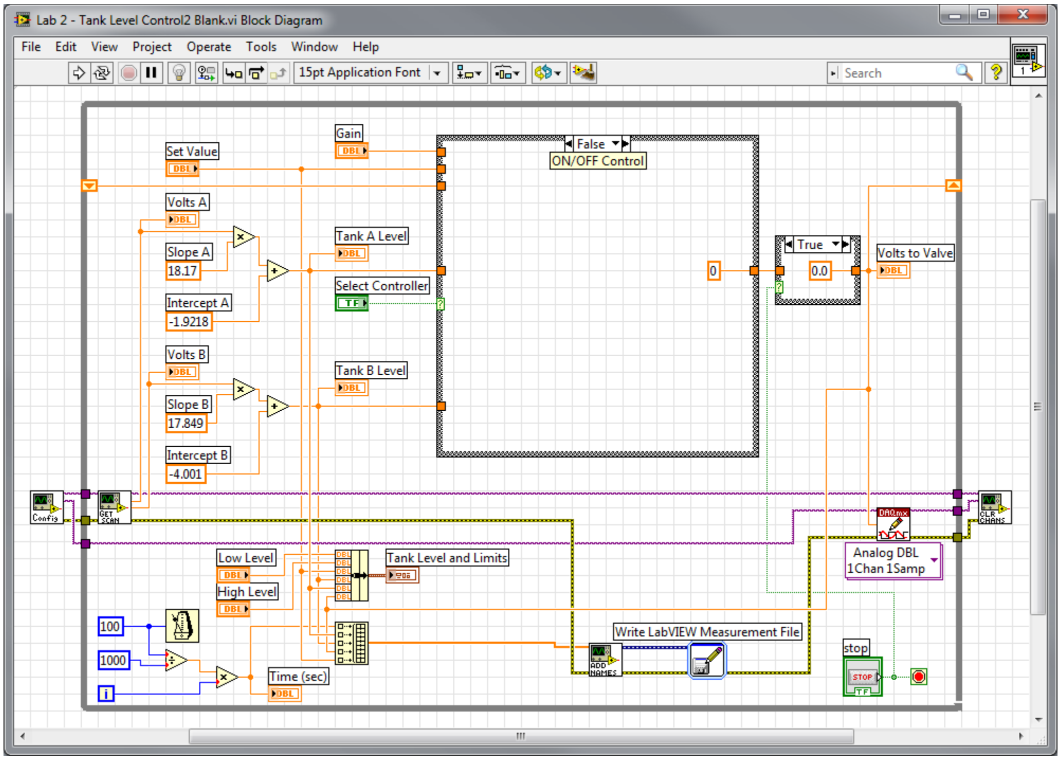


Figure 3. **Block Diagram of the Tank Level Control VI in the ON/OFF Control Case**

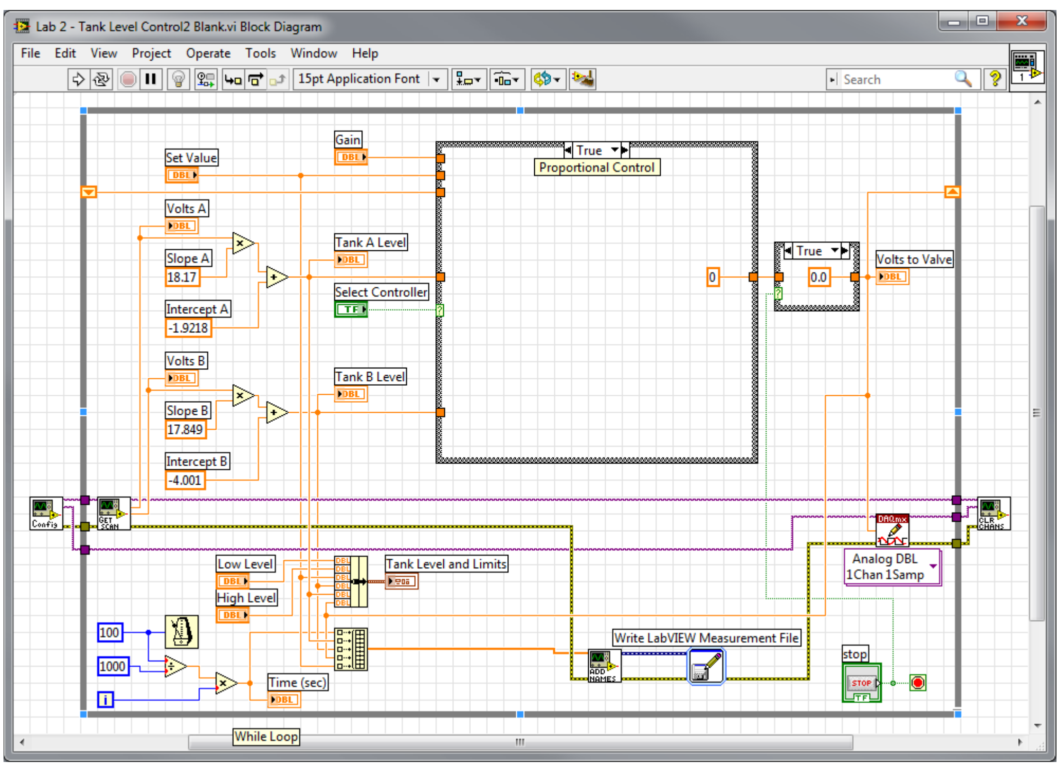


Figure 4. **Block Diagram of the Tank Level Control VI in the Proportional Control Case**

ON/OFF Control Algorithm

In the case of ON/OFF control, the level should be fluctuating within a range of high and low level limits supplied by the user. The ON/OFF control algorithm should function as follows:

1. If the acquired tank level is between the two limits, the last valve setting should be preserved.
2. If the tank level exceeds the high limit, the valve must be completely shut off by sending a signal of 0 volts.
3. If the tank level drops below the low limit, the valve is turned fully open by sending a signal of 10 volts.

Proportional Control Algorithm

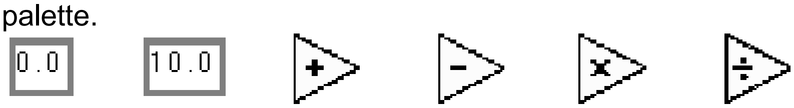
For proportional control, the user provides a set value for the desired tank level and an appropriate gain. The proportional control should function as follows:

1. The acquired tank level is first subtracted from the set value to get the error in level signal.
2. The error in level is then multiplied by the controller gain that converts from level units to volts.
3. Finally the resulting voltage signal must be checked to be within 0 and 10 volts. If it is less than 0, send a 0 voltage, and if it is higher than 10, use 10 volts.

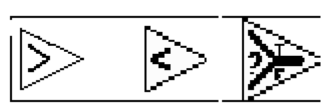
LabVIEW functions to use in the control algorithm

The following LabVIEW functions may be useful in the implementation of the control algorithms within the case structure corresponding to the selection of the controller:

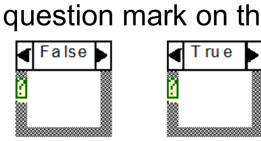
1. *Numeric Constants* and *Operators:* Found under the Numeric subpalette of the Functions palette.



2. *Comparison Operators:* Found under the Comparison subpalette of the Functions palette.



3. *Case Structures:* Found under the Structures subpalette of the Functions palette. Analogous to the If…Then…Else statements. The Case Structure has multiple subdiagrams of which only one subdiagram is visible at a time. A Boolean diagram identifier must be wired to the question mark on the structure border.



***Tip:** you may use the **"In-Range and Coerce"** structure as a convenience (look under All Functions->Comparison.)*

****Optional: Add a guage to show the voltage to the control valve.***

Calibration

Use the slope and intercept values you obtained in Lab 1 and insert them into the block diagram.

Single Tank Process Control

It is required to control the level in Tank B by controlling the flow through the proportional control valve. The liquid flows into Tank B through Inlet Valve B. Process Valve B should be fully open. Inlet Valve A and Valve AB should be closed. Assume the operating liquid height in Tank B is to be maintained at 7 inches. The Disturbance Valve should be initially closed.

ON/OFF Control Procedure

1. Start with Tank B empty.
2. Turn on the pump.
3. Select ON/OFF control and set the High and Low Limits to 8 and 6 inches respectively.
4. Run the VI.
5. Test the operation of the implemented ON/OFF algorithm (observe the voltage signal).
6. Examine and sketch the time response of the system.
7. Record the filling and draining times between the two limits.
8. Calculate the filling and draining rates (slope of the level – time curve).
9. Open the Disturbance Valve.
10. Examine and sketch the time response of the system to the disturbance.
11. Record the filling and draining times between the two limits.

Proportional Control Procedure

1. Start with Tank B empty.
2. Turn on the pump.
3. Select Proportional control with a set value of 7 inches and a gain of 1.0.
4. Run the VI.
5. Test the operation of the implemented proportional control algorithm.
6. Examine and sketch the time response of the system.
7. Record the steady state level of the response and the corresponding voltage signal.
8. Calculate the steady state error.
9. Open the Disturbance Valve.
10. Examine and sketch the time response of the system to the disturbance.
11. Find the steady state error and corresponding voltage signal in the case of the disturbance.
12. Close the Disturbance Valve.
13. Set the gain to 3.0 and repeat steps 6 – 12.
14. Set the gain to 5.0 and repeat steps 6 – 12.
15. With a gain of 5.0 and the Disturbance Valve closed, increase the set value to 9 inches. Examine the response of the system to this step input.

REPORT REQUIREMENTS

1. Have the TA inspect the developed VI and its operation.
2. Comment on any difficulties you encountered in building the VI.
3. For the ON/OFF control of the single tank system with and without disturbance, compare the filling and draining rates of the system in both cases. Sketch the system response in both cases on the same graph. Comment on the effect of the disturbance on the system response.
4. For the proportional control of the single tank system with and without disturbance, sketch the system response and compare the steady state error in both cases for each gain value. Comment on the effect of the controller gain on the steady state error. Why does the error get larger when the Disturbance Valve is opened? Use the relation between the system error and the voltage signal to the valve in your answer (*Hint: use the Appendix*). Sketch and comment on the response of the system to the step input. What order of system response can you use to model this system? Explain.
5. Discuss sources of error.

APPENDIX: Overview of feedback control

Two controllers are used in this laboratory. The first is ON/OFF control and is the simplest type of controller. The basic principle is to use a sensor to measure the value of the variable you are trying to control. For example, a thermometer may be used in your home heating system to measure temperature. The ON/OFF controller is simply ON whenever the measured value is below the set point (e.g. the temperature is below the value you set on your home thermostat), and off otherwise. In your home, the temperature will drop due to heat loss (furnace off), and rise due to the furnace (furnace on). This type of controller is also called "bang-bang" control since the controller cycles between *full on* & *full off*.

The concept of feedback is inherent in the controller. Feedback simply means the measured value is fed back into the controller and compared to the set point (also called reference value). In this laboratory, the sensor measures tank height, and the controller actuates the proportional control valve.

A more sophisticated controller is the Proportional Controller. This is similar to ON/OFF control in that the actuator is controlled to try to maintain a set value of the measured variable. But here the actuator is turned on a small amount if the measured value is only a small amount from the set point. The greater the difference between the measured value and the set point, the greater the actuator is activated. In other words, you need an actuator that is capable of providing a graduated set of outputs, not just on/off. (Most home heating systems have furnaces that only turn on/off, hence the use of ON/OFF control). The control valve used in this laboratory is capable of providing a range of output speeds, so a proportional controller can be used here.

The feedback in a proportional controller is also compared to the set point. In fact, the measured value is subtracted from the set point to get an "error signal". The error signal can be considered the difference between "what you want" and "what is actually happening". The error signal is sent to the actuator (with suitable amplification). When the set point is larger than the measured value, the error signal is positive. This means the actuator should be used to raise the system variable. When the set point is small than the measured value, the error signal is negative. This means the actuator should be used to drop the system variable. Since our valve cannot run in reverse, we simply turn off the pump for negative error signals (we do this by clipping the error signal to be only positive). Gravity then makes the water level drop.

A review of water level control is reprinted below from *System Dynamics, 4th edition, K. Ogata, 2004, Pearson-Prentice Hall.* The review is meant to answer "what is a first order system?", "what is proportional feedback?", "what is steady-state error?", "what is controller gain?". Although the review uses a water tank example, the notation and other details may be different than what is printed in Labs 1 and 2.

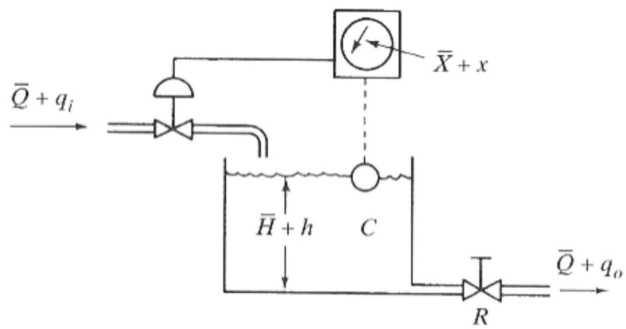


Figure 7–3(a) and
Figure 10–14 Liquid-level control system.

Mathematical modeling of liquid-level systems. In the mathematical modeling of liquid-level systems, we do not take inertance into consideration, because it is negligible. Instead, we characterize liquid-level systems in terms of resistance and capacitance. Let us now obtain a mathematical model of the liquid-level system shown in Figure 7–3(a). If the operating condition as to the head and flow rate varies little for the period considered, a mathematical model can easily be found in terms of resistance and capacitance. In the present analysis, we assume that the liquid outflow from the valve is turbulent.

Let us define

$\bar{H}$ = steady-state head (before any change has occurred), m
h = small deviation of head from its steady-state value, m
$\bar{Q}$ = steady-state flow rate (before any change has occurred), m^3/s
q_i = small deviation of inflow rate from its steady-state value, m^3/s
q_o = small deviation of outflow rate from its steady-state value, m^3/s

The change in the liquid stored in the tank during dt seconds is equal to the net inflow to the tank during the same dt seconds, so

$$C\,dh = (q_i - q_o)\,dt \tag{7–3}$$

where C is the capacitance of the tank.

The capacitance C of a tank is defined to be the change in quantity of stored liquid necessary to cause a unit change in the potential, or head. (The potential is the quantity that indicates the energy level of the system.) Thus,

$$C = \frac{\text{change in liquid stored}}{\text{change in head}} \frac{m^3}{m} \text{ or } m^2$$

Note that the capacity (m^3) and the capacitance (m^2) are different. The capacitance of the tank is equal to its cross-sectional area. If this is constant, the capacitance is constant for any head.

Note that if the operating condition varies little (i.e., if the changes in head and flow rate are small during the period of operation considered), then the resistance R may be considered constant during the entire period of operation.

In the present system, we defined h and q_o as small deviations from steady-state head and steady-state outflow rate, respectively. Thus,

$$dH = h, \qquad dQ = q_o$$

and the resistance R may be written as

$$R = \frac{dH}{dQ} = \frac{h}{q_o}$$

Substituting $q_o = h/R$ into Equation (7–3), we obtain

$$C\frac{dh}{dt} = q_i - \frac{h}{R}$$

or

$$RC\frac{dh}{dt} + h = Rq_i \tag{7–4}$$

Note that RC has the dimension of time and is the time constant of the system. Equation (7–4) is a linearized mathematical model for the system when h is considered the system output. Such a linearized mathematical model is valid, provided that changes in the head and flow rate from their respective steady-state values are small.

If q_o (the change in the outflow rate), rather than h (the change in head), is considered the system output, then another mathematical model may be obtained. Substituting $h = Rq_o$ into Equation (7–4) gives

$$RC\frac{dq_o}{dt} + q_o = q_i \tag{7–5}$$

which is also a linearized mathematical model for the system.

Analogous systems. The liquid-level system considered here is analogous to the electrical system shown in Figure 7–4(a). It is also analogous to the mechanical system shown in Figure 7–4(b). For the electrical system, a mathematical model is

$$RC\frac{de_o}{dt} + e_o = e_i \tag{7–6}$$

For the mechanical system, a mathematical model is

$$\frac{b}{k}\frac{dx_o}{dt} + x_o = x_i \tag{7–7}$$

Equations (7–5), (7–6), and (7–7) are of the same form; thus, they are analogous. Hence, the liquid-level system shown in Figure 7–3(a), the electrical system shown

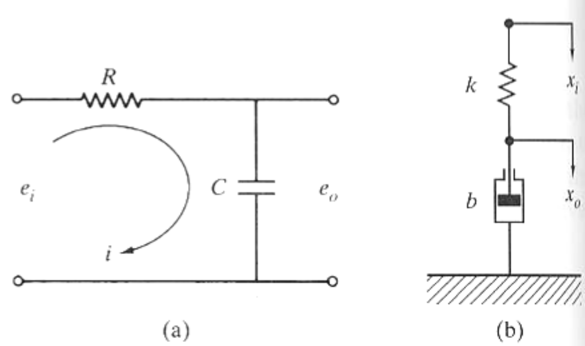


Figure 7–4 Systems analogous to the liquid-level system shown in Figure 7–3(a). (a) Electrical system; (b) mechanical system.

Proportional control of first-order system. Suppose that the controller in the liquid-level control system of Figure 10–14 is a proportional controller. Suppose also that the reference input to the system is $\overline{X}$. At $t = 0$, a change in the reference input is made from $\overline{X}$ to $\overline{X} + x$. Assume that all the variables shown in the diagram—x, q_i, h, and q_o—are measured from their respective steady-state values $\overline{X}$, $\overline{Q}$, $\overline{H}$, and $\overline{Q}$. Assume also that the magnitudes of the variables x, q_i, h, and q_o are sufficiently small, which means that the system can be approximated by a linear mathematical model.

Referring to Section 7–2, the following equation for the liquid-level system can be derived:

$$RC\frac{dh}{dt} + h = Rq_i \tag{10–5}$$

[See Equation (7–4).] So the transfer function between $H(s)$ and $Q_i(s)$ is found to be

$$\frac{H(s)}{Q_i(s)} = \frac{R}{RCs + 1} \tag{10–6}$$

Here, we assume that the gain K_v of the control valve is constant near the steady-state operating condition. Then, since the controller is a proportional one, the change in inflow rate q_i is proportional to the actuating error e (where $e = x - h$), or

$$q_i = K_pK_ve \tag{10–7}$$

where K_p is the gain of the proportional controller. In terms of Laplace-transformed quantities, Equation (10–7) becomes

$$Q_i(s) = K_pK_vE(s)$$

A block diagram of this system appears in Figure 10–15(a). To simplify our analysis, we assume that x and h are the same kind of signal with the same units, so that they can be compared directly. (Otherwise, we must insert a feedback transfer function K_b in the feedback path.) A simplified block diagram is given in Figure 10–15(b), where $K = K_pK_v$.

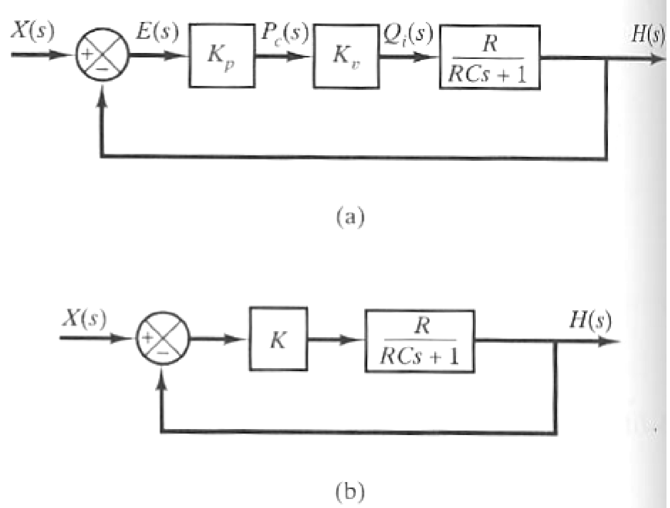


Figure 10–15 (a) Block diagram of the liquid-level control system shown in Figure 10–14; (b) simplified block diagram.

Next, we investigate the response $h(t)$ to a change in the reference input. We shall assume a unit-step change in $x(t)$. The closed-loop transfer function between $H(s)$ and $X(s)$ is given by

$$\frac{H(s)}{X(s)} = \frac{KR}{RCs + 1 + KR} \tag{10–8}$$

Since the Laplace transform of the unit-step function is $1/s$, substituting $X(s) = 1/s$ into Equation (10–8) gives

$$H(s) = \frac{KR}{RCs + 1 + KR}\frac{1}{s}$$

Then the expansion of $H(s)$ into partial fractions results in

$$H(s) = \frac{KR}{1 + KR}\left\{\frac{1}{s} - \frac{1}{s + [(1 + KR)/RC]}\right\} \tag{10–9}$$

Next, by taking the inverse Laplace transforms of both sides of Equation (10–9), we obtain the time solution

$$h(t) = \frac{KR}{1 + KR}(1 - e^{-t/T_1}) \qquad t \geq 0 \tag{10–10}$$

where

$$T_1 = \frac{RC}{1 + KR}$$

Notice that the time constant T_1 of the closed-loop system is different from the time constant RC of the liquid-level system alone.

The response curve $h(t)$ is plotted against t in Figure 10–16. From Equation (10–10), we see that, as t approaches infinity, the value of $h(t)$ approaches $KR/(1 + KR)$, or

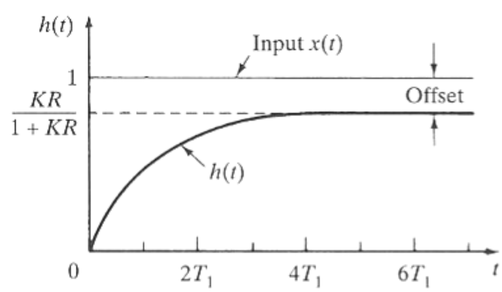


Figure 10–16 Unit-step response curve for the system shown in Figure 10–15(b).

$$h(\infty) = \frac{KR}{1 + KR}$$

Since $x(\infty) = 1$, there is a steady-state error of magnitude $1/(1 + KR)$. Such an error is called *offset*. The value of offset becomes smaller as the gain K becomes larger.