



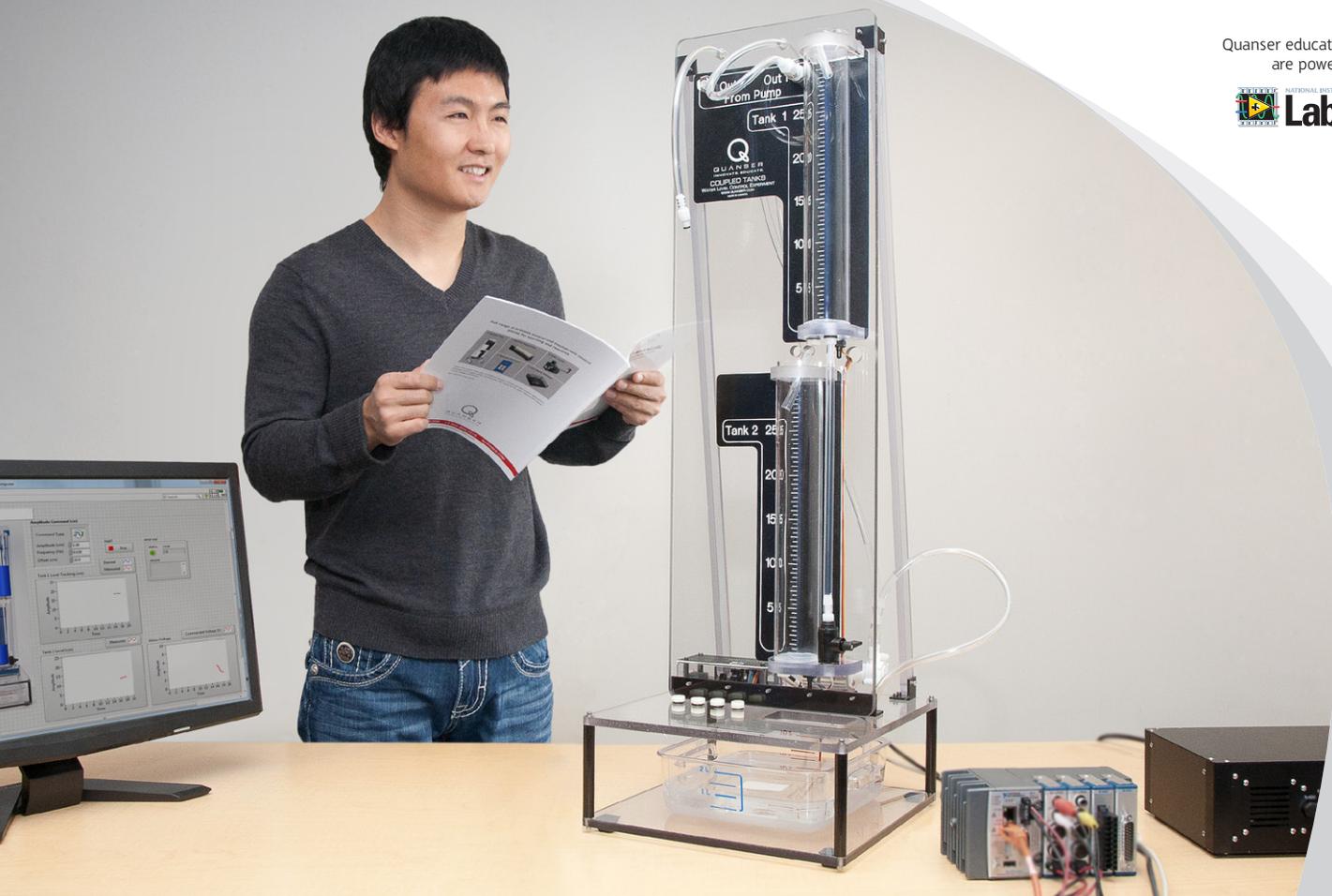
# STUDENT WORKBOOK

## Coupled Tanks Experiment for LabVIEW™ Users

Standardized for ABET\* Evaluation Criteria

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# 1 INTRODUCTION

The Coupled Tanks plant is a "Two-Tank" module consisting of a pump with a water basin and two tanks. The two tanks are mounted on the front plate such that flow from the first (i.e. upper) tank can flow, through an outlet orifice located at the bottom of the tank, into the second (i.e. lower) tank. Flow from the second tank flows into the main water reservoir. The pump thrusts water vertically to two quick-connect orifices "Out1" and "Out2". The two system variables are directly measured on the Coupled-Tank rig by pressure sensors and available for feedback. They are namely the water levels in tanks 1 and 2. A more detailed description is provided in [2]. To name a few, industrial applications of such Coupled-Tank configurations can be found in the processing system of petro-chemical, paper making, and/or water treatment plants.

During the course of this experiment, you will become familiar with the design and pole placement tuning of Proportional-plus-Integral-plus-Feedforward-based water level controllers. In the present laboratory, the Coupled-Tank system is used in two different configurations, namely configuration #1 and configuration #2, as described in [2]. In configuration #1, the objective is to control the water level in the top tank, i.e., tank #1, using the outflow from the pump. In configuration #2, the challenge is to control the water level in the bottom tank, i.e. tanks #2, from the water flow coming out of the top tank. Configuration #2 is an example of state coupled system.

## Topics Covered

- How to mathematically model the Coupled-Tank plant from first principles in order to obtain the two open-loop transfer functions characterizing the system, in the Laplace domain.
- How to linearize the obtained non-linear equation of motion about the quiescent point of operation.
- How to design, through pole placement, a Proportional-plus-Integral-plus-Feedforward-based controller for the Coupled-Tank system in order for it to meet the required design specifications for each configuration.
- How to implement each configuration controller(s) and evaluate its/their actual performance.

## Prerequisites

In order to successfully carry out this laboratory, the user should be familiar with the following:

1. See the system requirements in Section 5 for the required hardware and software.
2. Transfer function fundamentals, e.g., obtaining a transfer function from a differential equation.
3. Familiar with designing PID controllers.
4. Basics of [LabVIEW™](#) .

# 2 MODELING

## 2.1 Background

### 2.1.1 Configuration # 1 System Schematics

A schematic of the Coupled-Tank plant is represented in Figure 2.1, below. The Coupled-Tank system's nomenclature is provided in Appendix A. As illustrated in Figure 2.1, the positive direction of vertical level displacement is upwards, with the origin at the bottom of each tank (i.e. corresponding to an empty tank), as represented in Figure 3.2.

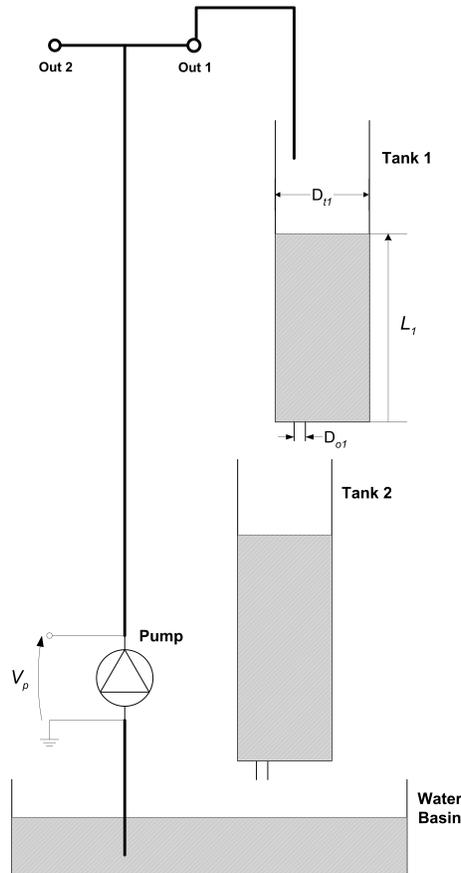


Figure 2.1: Schematic of Coupled Tank in Configuration #1.

### 2.1.2 Configuration # 1 Nonlinear Equation of Motion (EOM)

In order to derive the mathematical model of your Coupled-Tank system in configuration #1, it is reminded that the pump feeds into Tank 1 and that tank 2 is not considered at all. Therefore, the input to the process is the voltage to the pump  $V_P$  and its output is the water level in tank 1,  $L_1$ , (i.e. top tank).

The purpose of the present modelling session is to provide you with the system's open-loop transfer function,  $G1(s)$ , which in turn will be used to design an appropriate level controller. The obtained Equation of Motion, EOM, should be a function of the system's input and output, as previously defined.

Therefore, you should express the resulting EOM under the following format:

$$\frac{\partial L_1}{\partial t} = f(L_1, V_p)$$

where  $f$  denotes a function.

In deriving the Tank 1 EOM the mass balance principle can be applied to the water level in tank 1, i.e.,

$$A_{t1} \frac{\partial L_1}{\partial t} = F_{i1} - F_{o1} \quad (2.1)$$

where  $A_{t1}$  is the area of Tank 1.  $F_{i1}$  and  $F_{o1}$  are the inflow rate and outflow rate, respectively. The volumetric inflow rate to tank 1 is assumed to be directly proportional to the applied pump voltage, such that:

$$F_{i1} = K_p V_p$$

Applying Bernoulli's equation for small orifices, the outflow velocity from tank 1,  $v_{o1}$ , can be expressed by the following relationship:

$$v_{o1} = \sqrt{2gL_1}$$

### 2.1.3 Configuration # 1 EOM Linearization and Transfer Function

In order to design and implement a linear level controller for the tank 1 system, the open-loop Laplace transfer function should be derived. However by definition, such a transfer function can only represent the system's dynamics from a linear differential equation. Therefore, the nonlinear EOM of tank 1 should be linearized around a quiescent point of operation. By definition, static equilibrium at a nominal operating point  $(V_{p0}, L_{10})$  is characterized by the Tank 1 level being at a constant position  $L_{10}$  due to a constant water flow generated by constant pump voltage  $V_{p0}$ .

In the case of the water level in tank 1, the operating range corresponds to small departure heights,  $L_{11}$ , and small departure voltages,  $V_{p1}$ , from the desired equilibrium point  $(V_{p0}, L_{10})$ . Therefore,  $L_1$  and  $V_p$  can be expressed as the sum of two quantities, as shown below:

$$L_1 = L_{10} + L_{11}, \quad V_p = V_{p0} + V_{p1} \quad (2.2)$$

The obtained linearized EOM should be a function of the system's small deviations about its equilibrium point  $(V_{p0}, L_{10})$ . Therefore, one should express the resulting linear EOM under the following format:

$$\frac{\partial}{\partial t} L_{11} = f(L_{11}, V_{p1}) \quad (2.3)$$

where  $f$  denotes a function.

#### Example: Linearizing a Two-Variable Function

Here is an example of how to linearize a two-variable nonlinear function called  $f(z)$ . Variable  $z$  is defined

$$z^T = [z_1 \ z_2]$$

and  $f(z)$  is to be linearized about the operating point

$$z_0^T = [a \ b]$$

The linearized function is

$$f_z = f(z_0) + \left( \frac{\partial f(z)}{\partial z_1} \right) \Big|_{z=z_0} (z_1 - a) + \left( \frac{\partial f(z)}{\partial z_2} \right) \Big|_{z=z_0} (z_2 - b)$$

For a function,  $f$ , of two variables,  $L_1$  and  $V_p$ , a first-order approximation for small variations at a point  $(L_1, V_p) = (L_{10}, V_{p0})$  is given by the following Taylor's series approximation:

$$\frac{\partial^2}{\partial L_1 \partial V_p} f(L_1, V_p) \cong f(L_{10}, V_{p0}) + \left( \frac{\partial}{\partial L_1} f(L_{10}, V_{p0}) \right) (L_1 - L_{10}) + \left( \frac{\partial}{\partial V_p} f(L_{10}, V_{p0}) \right) (V_p - V_{p0}) \quad (2.4)$$

### Transfer Function

From the linear equation of motion, the system's open-loop transfer function in the Laplace domain can be defined by the following relationship:

$$G_1(s) = \frac{L_{11}(s)}{V_{p1}(s)} \quad (2.5)$$

The desired open-loop transfer function for the Coupled-Tank's tank 1 system is the following:

$$G_1(s) = \frac{K_{dc1}}{\tau_1 s + 1} \quad (2.6)$$

where  $K_{dc1}$  is the open-loop transfer function DC gain, and  $\tau_1$  is the time constant.

As a remark, it is obvious that linearized models, such as the Coupled-Tank tank 1's voltage-to-level transfer function, are only approximate models. Therefore, they should be treated as such and used with appropriate caution, that is to say within the valid operating range and/or conditions. However for the scope of this lab, Equation 2.5 is assumed valid over the pump voltage and tank 1 water level entire operating range,  $V_{p\_peak}$  and  $L_{1\_max}$ , respectively.

## 2.1.4 Configuration #2 System Schematics

A schematic of the Coupled-Tank plant is represented in Figure 2.2, below. The Coupled-Tank system's nomenclature is provided in Appendix A. As illustrated in Figure 2.2, the positive direction of vertical level displacement is upwards, with the origin at the bottom of each tank (i.e. corresponding to an empty tank), as represented in Figure 2.2.

## 2.1.5 Configuration #2, Nonlinear Equation of Motion (EOM)

This section explains the mathematical model of your Coupled-Tank system in configuration #2, as described in Reference [1]. It is reminded that in configuration #2, the pump feeds into tank 1, which in turn feeds into tank 2. As far as tank 1 is concerned, the same equations as the ones explained in Section 2.1.2 and Section 2.1.3 will apply. However, the water level Equation Of Motion (EOM) in tank 2 still needs to be derived. The input to the tank 2 process is the water level,  $L_1$ , in tank 1 (generating the outflow feeding tank 2) and its output variable is the water level,  $L_2$ , in tank 2 (i.e. bottom tank). The purpose of the present modelling session is to guide you with the system's open-loop transfer function,  $G_2(s)$ , which in turn will be used to design an appropriate level controller. The obtained EOM should be a function of the system's input and output, as previously defined.

Therefore, you should express the resulting EOM under the following format:

$$\frac{\partial L_2}{\partial t} = f(L_2, L_1)$$

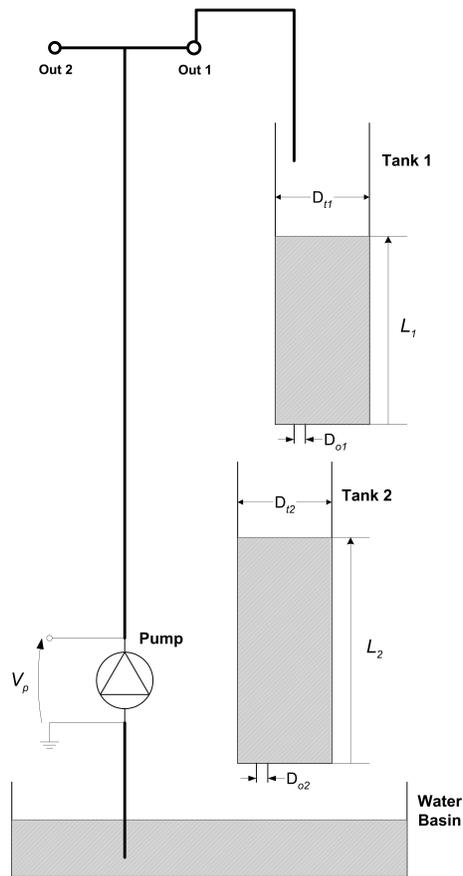


Figure 2.2: Schematic of Coupled Tank in configuration #1.

where  $f$  denotes a function.

In deriving the tank #2 EOM the mass balance principle can be applied to the water level in tank 2 as follows

$$A_{t2} \frac{\partial L_2}{\partial t} = F_{i2} - F_{o2}$$

where  $A_{t2}$  is the area of tank 2.  $F_{i2}$  and  $F_{o2}$  are the inflow rate and outflow rate, respectively.

The volumetric inflow rate to tank 2 is equal to the volumetric outflow rate from tank 1, that is to say:

$$F_{i2} = F_{o1}$$

Applying Bernoulli's equation for small orifices, the outflow velocity from tank 2,  $v_{o2}$ , can be expressed by the following relationship:

$$v_{o2} = \sqrt{2gL_2}$$

### 2.1.6 Configuration #2 EOM Linearization and Transfer Function

In order to design and implement a linear level controller for the tank 2 system, the Laplace open-loop transfer function should be derived. However by definition, such a transfer function can only represent the system's dynamics from a linear differential equation. Therefore, the nonlinear EOM of tank 2 should be linearized around a quiescent point of operation.

In the case of the water level in tank 2, the operating range corresponds to small departure heights,  $L_{11}$  and  $L_{21}$ , from the desired equilibrium point  $(L_{10}, L_{20})$ . Therefore,  $L_2$  and  $L_1$  can be expressed as the sum of two quantities, as shown below:

$$L_2 = L_{20} + L_{21}, \quad L_1 = L_{10} + L_{11} \quad (2.7)$$

The obtained linearized EOM should be a function of the system's small deviations about its equilibrium point  $(L_{20}, L_{10})$ . Therefore, you should express the resulting linear EOM under the following format:

$$\frac{\partial}{\partial t} L_{21} = f(L_{11}, L_{21}) \quad (2.8)$$

where  $f$  denotes a function.

For a function,  $f$ , of two variables,  $L_1$  and  $L_2$ , a first-order approximation for small variations at a point  $(L_1, L_2) = (L_{10}, L_{20})$  is given by the following Taylor's series approximation:

$$\frac{\partial^2}{\partial L_1 \partial L_2} f(L_1, L_2) \cong f(L_{10}, L_{20}) + \left( \frac{\partial}{\partial L_1} f(L_{10}, L_{20}) \right) (L_1 - L_{10}) + \left( \frac{\partial}{\partial L_2} f(L_{10}, L_{20}) \right) (L_2 - L_{20}) \quad (2.9)$$

### Transfer Function

From the linear equation of motion, the system's open-loop transfer function in the Laplace domain can be defined by the following relationship:

$$G_2(s) = \frac{L_{21}(s)}{L_{11}(s)} \quad (2.10)$$

the desired open-loop transfer function for the Coupled-Tank's tank 2 system, such that:

$$G_2(s) = \frac{K_{dc2}}{\tau_2 s + 1} \quad (2.11)$$

where  $K_{dc2}$  is the open-loop transfer function DC gain, and  $\tau_2$  is the time constant.

As a remark, it is obvious that linearized models, such as the Coupled-Tank's tank 2 level-to-level transfer function, are only approximate models. Therefore, they should be treated as such and used with appropriate caution, that is to say within the valid operating range and/or conditions. However for the scope of this lab, Equation 2.10 is assumed valid over tank 1 and tank 2 water level entire range of motion,  $L_{1\_max}$  and  $L_{2\_max}$ , respectively.

## 2.2 Pre-Lab Questions

Answer the following questions:

1. Using the notations and conventions described in Figure 2 derive the Equation Of Motion (EOM) characterizing the dynamics of tank 1. Is the tank 1 system's EOM linear?

**Hint:** The outflow rate from tank 1,  $F_{o1}$ , can be expressed by:

$$F_{o1} = A_{o1}v_{o1} \quad (2.12)$$

2. The nominal pump voltage  $V_{p0}$  for the pump-tank 1 pair can be determined at the system's static equilibrium. By definition, static equilibrium at a nominal operating point  $(V_{p0}, L_{10})$  is characterized by the water in tank 1 being at a constant position level  $L_{10}$  due to the constant inflow rate generated by  $V_{p0}$ . Express the static equilibrium voltage  $V_{p0}$  as a function of the system's desired equilibrium level  $L_{10}$  and the pump flow constant  $K_p$ . Using the system's specifications given in the Coupled Tanks User Manual ([2]) and the desired design requirements in Section 3.1.1, evaluate  $V_{p0}$  parametrically.
3. Linearize tank 1 water level's EOM found in Question #1 about the quiescent operating point  $(V_{p0}, L_{10})$ .
4. Determine from the previously obtained linear equation of motion, the system's open-loop transfer function in the Laplace domain as defined in Equation 2.5 and Equation 2.6. Express the open-loop transfer function DC gain,  $K_{dc1}$ , and time constant,  $\tau_1$ , as functions of  $L_{10}$  and the system parameters. What is the order and type of the system? Is it stable? Evaluate  $K_{dc1}$  and  $\tau_1$  according to system's specifications given in the Coupled Tanks User Manual ([2]) and the desired design requirements in Section 3.1.1.
5. Using the notations and conventions described in Figure 2.2, derive the Equation Of Motion (EOM) characterizing the dynamics of tank 2. Is the tank 2 system's EOM linear?

**Hint:** The outflow rate from tank 2,  $F_{o2}$ , can be expressed by:

$$F_{o2} = A_{o2}v_{o2} \quad (2.13)$$

6. The nominal water level  $L_{10}$  for the tank1-tank2 pair can be determined at the system's static equilibrium. By definition, static equilibrium at a nominal operating point  $(L_{10}, L_{20})$  is characterized by the water in tank 2 being at a constant position level  $L_{20}$  due to the constant inflow rate generated from the top tank by  $L_{10}$ . Express the static equilibrium level  $L_{10}$  as a function of the system's desired equilibrium level  $L_{20}$  and the system's parameters. Using the system's specifications given in the Coupled Tanks User Manual ([2]) and the desired design requirements in Section 4.1.1, evaluate  $L_{10}$ .
7. Linearize tank 2 water level's EOM found in Question #5 about the quiescent operating point  $(L_{10}, L_{20})$ .
8. Determine from the previously obtained linear equation of motion, the system's open-loop transfer function in the Laplace domain, as defined in Equation 2.10 and Equation 2.11. Express the open-loop transfer function DC gain,  $K_{dc2}$ , and time constant,  $\tau_2$ , as functions of  $L_{10}$ ,  $L_{20}$ , and the system parameters. What is the order and type of the system? Is it stable? Evaluate  $K_{dc2}$  and  $\tau_2$  according to system's specifications given in the Coupled Tanks User Manual ([2]) and the desired design requirements in Section 4.1.1.

# 3 TANK 1 LEVEL CONTROL

## 3.1 Background

### 3.1.1 Specifications

In configuration #1, a control is designed to regulate the water level (or height) of tank #1 using the pump voltage. The control is based on a Proportional-Integral-Feedforward scheme (PI-FF). Given a  $\pm 1$  cm square wave level setpoint (about the operating point), the level in tank 1 should satisfy the following design performance requirements:

1. Operating level in tank 1 at 15 cm:  $L_{10} = 15$  cm.
2. Percent overshoot less than 10%:  $PO_1 \leq 11$  %.
3. 2% settling time less than 5 seconds:  $t_{s\_1} \leq 5.0$  s.
4. No steady-state error:  $e_{ss} = 0$  cm.

### 3.1.2 Tank 1 Level Controller Design: Pole Placement

For zero steady-state error, tank 1 water level is controlled by means of a Proportional-plus-Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in Figure 3.1, below, the voltage feedforward action is characterized by:

$$V_{p\_ff} = K_{ff\_1} \sqrt{L_{r\_1}} \quad (3.1)$$

and

$$V_p = V_{p1} + V_{p\_ff} \quad (3.2)$$

As it can be seen in Figure 3.1, the feedforward action is necessary since the PI control system is designed to compensate for small variations (a.k.a. disturbances) from the linearized operating point ( $V_{p0}, L_{10}$ ). In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 1 bottom outlet orifice, the PI controller compensates for dynamic disturbances.

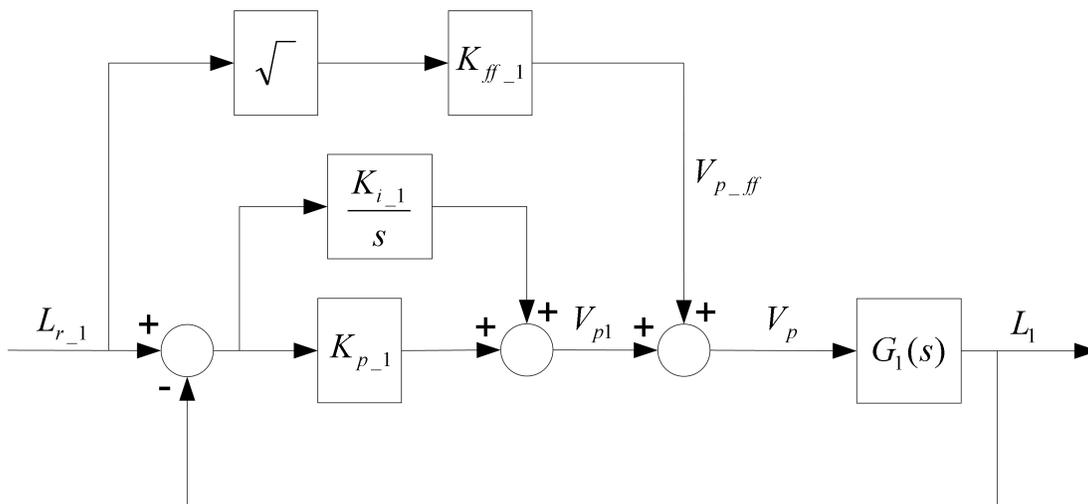


Figure 3.1: Tank 1 Water Level PI-plus-Feedforward Control Loop.

The open-loop transfer function  $G_1(s)$  takes into account the dynamics of the tank 1 water level loop, as characterized by Equation 2.5. However, due to the presence of the feedforward loop,  $G_1(s)$  can also be written as follows:

$$G_1(s) = \frac{L_1(s)}{V_{p1}(s)} \quad (3.3)$$

### 3.1.3 Second-Order Response

The block diagram shown in Figure 3.2 is a general unity feedback system with compensator, i.e., controller  $C(s)$  and a transfer function representing the plant,  $P(s)$ . The measured output,  $Y(s)$ , is supposed to track the reference signal  $R(s)$  and the tracking has to match to certain desired specifications.

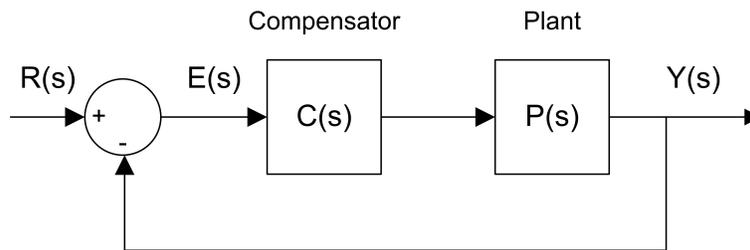


Figure 3.2: Unity feedback system.

The output of this system can be written as:

$$Y(s) = C(s) P(s) (R(s) - Y(s))$$

By solving for  $Y(s)$ , we can find the closed-loop transfer function:

$$\frac{Y(s)}{R(s)} = \frac{C(s) P(s)}{1 + C(s) P(s)}$$

The input-output relation in the time-domain for a proportional-integral (PI) controller is

$$u = K_p(r - y) + \frac{K_i(r - y)}{s} \quad (3.4)$$

where  $K_p$  is the proportional gain and  $K_i$  is the integral gain.

In fact, when a first order system is placed in series with PI compensator in the feedback loop as in Figure 3.2, the resulting closed-loop transfer function can be expressed as:

$$\frac{Y(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (3.5)$$

where  $\omega_n$  is the natural frequency and  $\zeta$  is the damping ratio. This is called the *standard second-order* transfer function. Its response properties depend on the values of  $\omega_n$  and  $\zeta$ .

#### Peak Time and Overshoot

Consider a second-order system as shown in Equation 3.5 subjected to a step input given by

$$R(s) = \frac{R_0}{s} \quad (3.6)$$

with a step amplitude of  $R_0 = 1.5$ . The system response to this input is shown in Figure 3.3, where the red trace is the response (output),  $y(t)$ , and the blue trace is the step input  $r(t)$ .

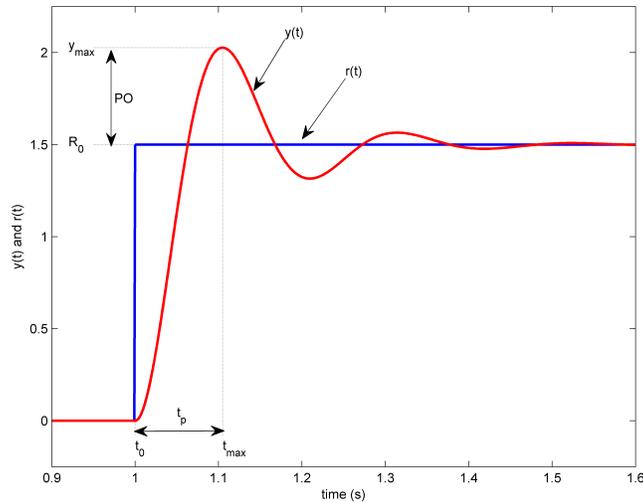


Figure 3.3: Standard second-order step response.

The maximum value of the response is denoted by the variable  $y_{max}$  and it occurs at a time  $t_{max}$ . For a response similar to Figure 3.3, the percent overshoot is found using

$$PO = \frac{100 (y_{max} - R_0)}{R_0} \quad (3.7)$$

From the initial step time,  $t_0$ , the time it takes for the response to reach its maximum value is

$$t_p = t_{max} - t_0 \quad (3.8)$$

This is called the *peak time* of the system.

In a second-order system, the amount of overshoot depends solely on the damping ratio parameter and it can be calculated using the equation

$$PO = 100 e^{\left(-\frac{\pi \zeta}{\sqrt{1-\zeta^2}}\right)} \quad (3.9)$$

The peak time depends on both the damping ratio and natural frequency of the system and it can be derived as

$$t_p = \frac{\pi}{\omega_n \sqrt{1-\zeta^2}} \quad (3.10)$$

Tank 1 level response 2% Settling Time can be expressed as follows:

$$t_s = \frac{4}{\zeta \omega} \quad (3.11)$$

Generally speaking, the damping ratio affects the shape of the response while the natural frequency affects the speed of the response.

## 3.2 Pre-Lab Questions

1. Analyze tank 1 water level closed-loop system at the static equilibrium point  $(V_{p0}, L_{10})$  and determine and evaluate the voltage feedforward gain,  $K_{ff-1}$ , as defined by Equation 3.1.
2. Using tank 1 voltage-to-level transfer function  $G_1(s)$  determined in Section 2.2 and the control scheme block diagram illustrated in Figure 3.1, derive the normalized characteristic equation of the water level closed-loop system.

**Hint#1:** The feedforward gain  $K_{ff-1}$  does not influence the system characteristic equation. Therefore, the feedforward action can be neglected for the purpose of determining the denominator of the closed-loop transfer function. Block diagram reduction can be carried out.

**Hint#2:** The system's normalized characteristic equation should be a function of the PI level controller gains,  $K_{p-1}$ , and  $K_{i-1}$ , and system's parameters,  $K_{dc-1}$  and  $\tau_1$ .

3. By identifying the controller gains  $K_{p-1}$  and  $K_{i-1}$ , fit the obtained characteristic equation to the second-order standard form expressed below:

$$s^2 + 2\zeta_1\omega_{n1}s + \omega_{n1}^2 = 0 \quad (3.12)$$

Determine  $K_{p-1}$  and  $K_{i-1}$  as functions of the parameters  $\omega_{n1}$ ,  $\zeta_1$ ,  $K_{dc-1}$ , and  $\tau_1$  using Equation 3.5.

4. Determine the numerical values for  $K_{p-1}$  and  $K_{i-1}$  in order for the tank 1 system to meet the closed-loop desired specifications, as previously stated.

## 3.3 Lab Experiments

### 3.3.1 Objectives

- Tune through pole placement the PI-plus-feedforward controller for the actual water level in tank 1 of the Coupled-Tank system.
- Implement the PI-plus-feedforward control loop for the actual Coupled-Tank's tank 1 level.
- Run the obtained PI-plus-feedforward level controller and compare the actual response against the controller design specifications.
- Run the system's simulation simultaneously, at every sampling period, in order to compare the actual and simulated level responses.

### 3.3.2 Tank 1 Level Control Simulation

#### Experimental Setup

The *Coupled Tanks - Tank1 Level Control simulation* VI shown in Figure 3.4 is used to perform tank 1 level control simulation exercises in this laboratory.

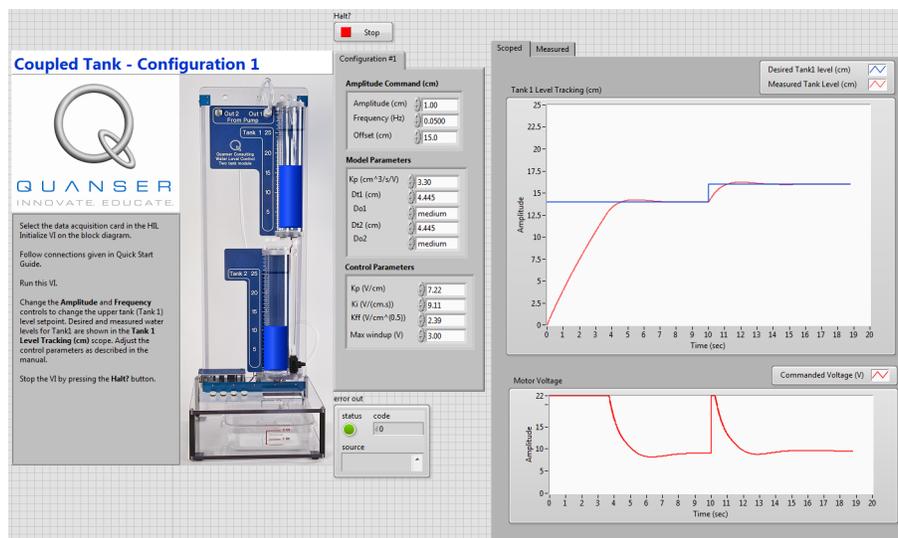


Figure 3.4: VI used to run PI-FF control Simulation on Coupled Tanks system in configuration #1.

**IMPORTANT:** Before you can conduct these simulations, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 5 to configure the lab files first.

Follow this procedure:

1. In *Coupled Tanks.lvproj*, open *Coupled Tanks- Tank1 Level Control Simulation.vi*. The model implements the system's simulation Proportional-plus-Integral (PI) closed-loop with feedforward action, as studied in Section 3.1.2. To familiarize yourself with the diagram, it is suggested that you open the model subsystems to get a better idea of their composing blocks as well as take note of the I/O connections.
2. To generate a square wave that goes between 14 and 16 cm for the tank 1 level reference, go to the *Amplitude Command (cm)* section and set the controls to the following:
  - Amplitude = 1 cm

- Frequency = 0.02 Hz
- Offset = 15 cm

The total level setpoint for tank 1 should result to be a square wave of  $\pm 1$ cm around the desired equilibrium level  $L_{10}$

3. Enter the proportional, integral, and feedforward control gains found in Section 3.2 in the  $kp\_1$ ,  $ki\_1$ , and  $kff\_1$  controls in the *Control Parameters* section on the front panel. Have your lab assistant check your values.
4. Run the VI.
5. The VI should start the Coupled Tanks simulation filling tank 1 up to its operating level  $L_{10}$ . Then after a 15-second settling delay (in order to stabilize the system at its operating point), the water level in tank 1 should start tracking the desired  $\pm 1$ cm square wave setpoint around the desired operating level  $L_{10}$ . The corresponding commanded pump voltage, which is proportional to the control effort spent, can also be monitored and plotted on-line.
6. Attach plots showing the *Implemented Tank 1 Level Control* response and the input voltage.
7. Assess the actual performance of the level response and compare it to the design requirements. Measure your response actual percent overshoot and settling time. Are the design specifications satisfied? Explain. If your level response does not meet the desired design specifications, review your PI-plus-Feedforward gain calculations and/or alter the closed-loop pole locations until they do. If you are still unable to achieve the required performance level, ask your T.A. for advice. Does the response satisfy the specifications given in Section 3.1.1?

**Hint:** Use the graph cursors in the *Measure* tab to take measurements.

### 3.3.3 Tank 1 Level Control Implementation

#### Experimental Setup

The *Coupled Tanks Tank1 Level Control* VI shown in Figure 3.5 is used to perform tank 1 level control exercises in this laboratory. This VI interfaces with the pump and pressure sensors of the Coupled Tanks system.

Note that a first-order low-pass filter with a cut-off frequency of 2.5 Hz is added to the output signal of the tank 1 level pressure sensor. This filter is necessary to attenuate the high-frequency noise content of the level measurement. Such a measurement noise is mostly created by the sensor's environment consisting of turbulent flow and circulating air bubbles. Although introducing a short delay in the signals, low-pass filtering allows for higher controller gains in the closed-loop system, and therefore for higher performance. Moreover, as a safety watchdog, the controller will stop if the water level in either tank 1 or tank 2 goes beyond 27 cm.

**IMPORTANT:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 5 to configure the lab files first.

Follow this procedure:

1. In *Coupled Tanks.lvproj*, open *Coupled Tanks Tank1 Level Control.vi*. The model implements the system's actual Proportional-plus-Integral (PI) closed-loop with feedforward action. To familiarize yourself with the diagram, it is suggested that you open the model subsystems to get a better idea of their composing blocks as well as take note of the I/O connections.
2. To generate a square wave that goes between 14 and 16 cm for the tank 1 level reference, go to the *Amplitude Command (cm)* section and set the controls to the following:
  - Amplitude = 1 cm
  - Frequency = 0.02 Hz
  - Offset = 15 cm

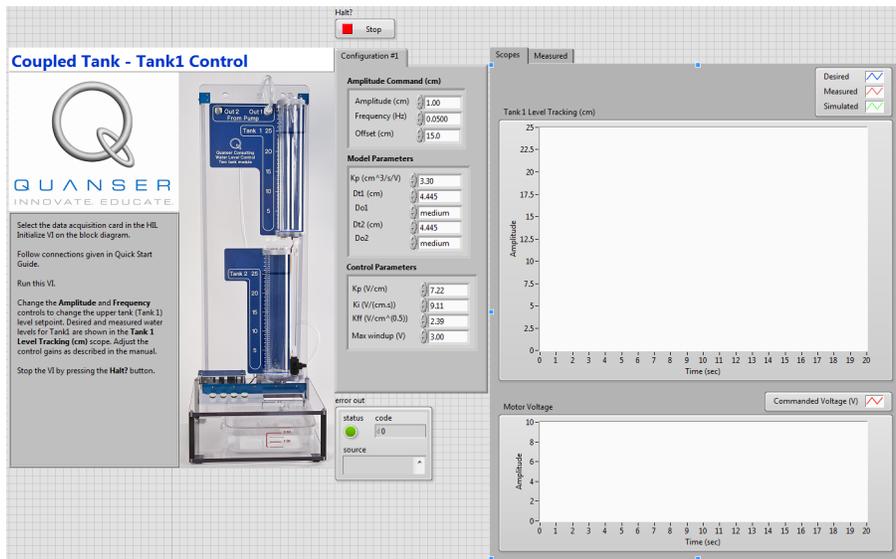


Figure 3.5: VI used to run PI-FF control on Coupled Tanks system in configuration #1.

The total level setpoint for tank 1 should result to be a square wave of  $\pm 1$  cm around the desired equilibrium level  $L_{10}$

3. Enter the proportional, integral, and feedforward control gains found in Section 3.2 in the  $K_p$ ,  $K_i$ , and  $K_{ff}$  controls in the *Control Parameters* section on the front panel. Have your lab assistant check your values.
4. Run the VI. The pump should start running and filling up tank 1 to its operating level,  $L_{10}$ . After a settling delay, the water level in tank 1 should begin tracking the  $\pm 1$  cm square wave setpoint (about operating level  $L_{10}$ ).
5. Attach plots showing the *Implemented Tank 1 Level Control* response and the input voltage.
6. Assess the actual performance of the level response and compare it to the design requirements. Measure your response actual percent overshoot and settling time. Are the design specifications satisfied? Explain. If your level response does not meet the desired design specifications, review your PI-plus-Feedforward gain calculations and/or alter the closed-loop pole locations until they do. If you are still unable to achieve the required performance level, ask your lab instructors for advice. Does the response satisfy the specifications given in Section 3.1.1?

**Hint:** Use the graph cursors in the *Measure* tab to take measurements.

7. Specifically discuss in your lab report the following points:
  - How does your actual tank 1 level compare to the simulated response?
  - From the plot of the actual level response, measure your system settling time and percentage overshoot. Are the values in agreement with the design specifications? If not exactly, find some of the possible reasons.
  - Include in your lab report your final values for  $K_{p\_1}$ ,  $K_{i\_1}$ , and  $K_{ff\_1}$  as well as the resulting response plot of the actual and theoretical  $L_1$  versus  $L_{r\_1}$ . Also include from the same run the corresponding plot of  $V_p$ . Ensure to properly document all your results and observations before moving on to the next section.
  - You can now proceed to the next section, which deals with the actual implementation of your PI-plus-Feedforward level controller for tank 2 of the Coupled-Tank system in configuration #2.

## 3.4 Results

Fill out Table 3.1 with your answers from your control lab results - both simulation and implementation.

Description	Symbol	Value	Units
<b>Pre Lab Questions</b>			
<i>Tank 1 Control Gains</i>			
Feed Forward Control Gain	$K_{ff1}$		$V/\sqrt{cm}$
Proportional Control Gain	$k_{p1}$		V/cm
Integral Control Gain	$k_{i1}$		V/(cm-s)
<b>Tank 2 Control Simulation</b>			
Steady-state error	$e_{ss}$		cm
Settling time	$t_{s1}$		s
Percent overshoot	$PO_1$		%
<b>Tank 2 Control Implementation</b>			
Steady-state error	$e_{ss}$		cm
Settling time	$t_{s1}$		s
Percent overshoot	$PO_1$		%

Table 3.1: Results

# 4 TANK 2 LEVEL CONTROL

## 4.1 Background

### 4.1.1 Specifications

In configuration #2, the pump feeds tank 1 and tank 1 feeds tank 2. The designed closed-loop system is to control the water level in tank 2 (i.e. the bottom tank) from the water flow coming out of tank 1, located above it. Similarly to configuration #1, the control scheme is based on a Proportional-plus-Integral-plus-Feedforward law.

In response to a desired  $\pm 1$  cm square wave level setpoint from tank 2 equilibrium level position, the water height behaviour should satisfy the following design performance requirements:

1. Tank 2 operating level at 15 cm:  $L_{20} = 15$  cm.
2. Percent overshoot should be less than or equal to 10%:  $PO_2 \leq 10.0$  %.
3. 2% settling time less than 20 seconds:  $t_{s,2} \leq 20.0$  s.
4. No steady-state error:  $e_{ss,2} = 0$  cm.

### 4.1.2 Tank 2 Level Controller Design: Pole Placement

For zero steady-state error, tank 1 water level is controlled by means of a Proportional-plus-Integral (PI) closed-loop scheme with the addition of a feedforward action, as illustrated in Figure 4.1, below.

In the block diagram depicted in Figure 4.1, the water level in tank 1 is controlled by means of the closed-loop system previously designed in Section 3.1. This is represented by the tank 1 closed-loop transfer function defined below:

$$T_1(s) = \frac{L_1(s)}{L_{r_1}(s)} \quad (4.1)$$

Such a subsystem represents an inner (or nested) level loop. In order to achieve a good overall stability with such a configuration, the inner level loop (i.e. tank 1 closed-loop system) must be much faster than the outer level loop. This constraint is met by the previously stated controller design specifications, where  $t_{s_1} \leq t_{s_2}$ .

However for the sake of simplicity in the present analysis, the water level dynamics in tank 1 are neglected. Therefore, it is assumed hereafter that:

$$L_1(t) = L_{r_1}(t) \quad i.e. \quad T_1(s) = 1 \quad (4.2)$$

Furthermore as depicted in Figure 4.1, the level feedforward action is characterized by:

$$L_{ff_1} = K_{ff_2} L_{r_2} \quad (4.3)$$

and

$$L_1 = L_{11} + L_{ff_1} \quad (4.4)$$

The level feedforward action, as seen in Figure 4.1, is necessary since the PI control system is only designed to compensate for small variations (a.k.a. disturbances) from the linearized operating point  $L_{10}$ ,  $L_{20}$ . In other words, while the feedforward action compensates for the water withdrawal (due to gravity) through tank 2's bottom outlet orifice, the PI controller compensates for dynamic disturbances.

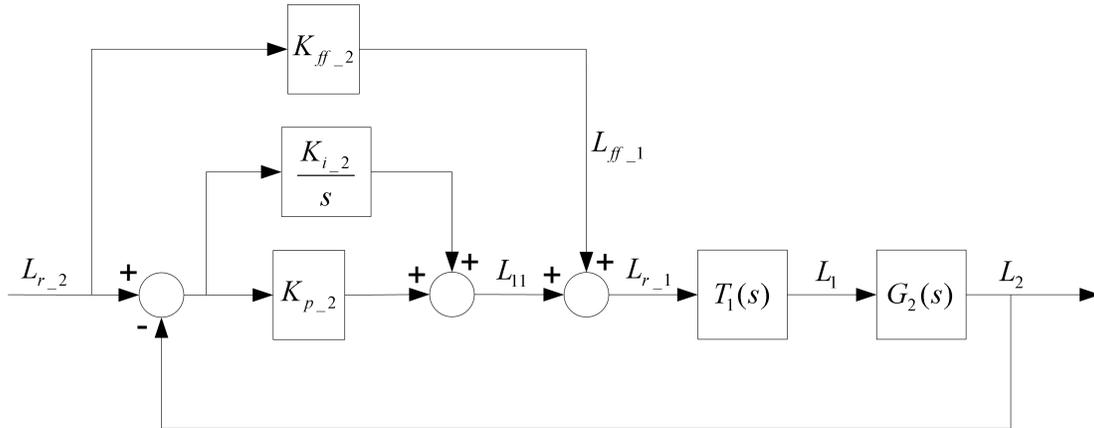


Figure 4.1: Tank 2 Water Level PI-plus-Feedforward Control Loop.

The open-loop transfer function  $G_2(s)$  takes into account the dynamics of the tank 2 water level loop, as characterized by Equation 2.10. However, due to the presence of the feedforward loop and the simplifying assumption expressed by Equation 4.2,  $G_2(s)$  can also be written as follows:

$$G_2(s) = \frac{L_2(s)}{L_1(s)} \quad (4.5)$$

## 4.2 Pre-Lab Questions

1. Analyze tank 2 water level closed-loop system at the static equilibrium point  $(L_{10}, L_{20})$  and determine and evaluate the voltage feedforward gain,  $K_{ff\_2}$ , as defined by Equation 4.3.
2. Using tank 2 voltage-to-level transfer function  $G_2(s)$  determined in Section 2 and the control scheme block diagram illustrated in Figure 4.1, derive the normalized characteristic equation of the water level closed-loop system.

**Hint#1:** Block diagram reduction can be carried out.

**Hint#2:** The system's normalized characteristic equation should be a function of the PI level controller gains,  $K_{p\_2}$ , and  $K_{i\_2}$ , and system's parameters,  $K_{dc\_2}$  and  $\tau_2$ .

3. By identifying the controller gains  $K_{p\_2}$  and  $K_{i\_2}$ , fit the obtained characteristic equation to the standard second-order equation:  $s^2 + 2\zeta_2\omega_{n2}s + \omega_{n2}^2 = 0$ . Determine  $K_{p\_2}$  and  $K_{i_2}$  as functions of the parameters  $\omega_{n2}$ ,  $\zeta_2$ ,  $K_{dc\_2}$ , and  $\tau_2$ .
4. Determine the numerical values for  $K_{p\_2}$  and  $K_{i\_2}$  in order for the tank 2 system to meet the closed-loop desired specifications, as previously stated.

## 4.3 Lab Experiments

### 4.3.1 Objectives

- Tune through pole placement the PI-plus-Feedforward controller for the actual water level of the Coupled-Tank system's tank 2.
- Implement the PI-plus-Feedforward control loop for the actual tank 2 water level.
- Run the obtained Feedforward-plus-PI level controller and compare the actual response against the controller design specifications.
- Run the system's simulation simultaneously, at every sampling period, in order to compare the actual and simulated level responses.
- Investigate the effect of the nested PI-plus-Feedforward level control loop implemented for tank 2.

### 4.3.2 Tank 2 Level Control Simulation

#### Experimental Setup

The *Coupled Tanks - Tank2 Level Control simulation* VI shown in Figure 4.2 is used to perform tank 2 level control simulation exercises in this laboratory.

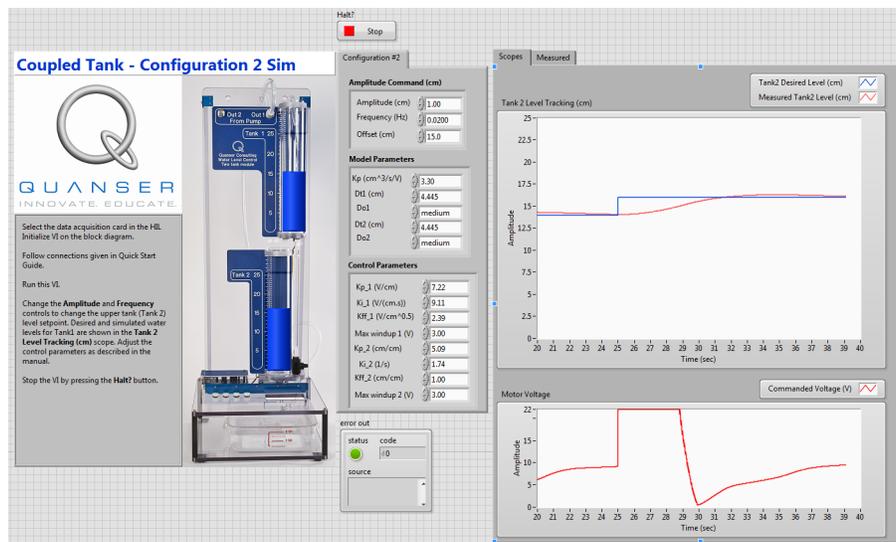


Figure 4.2: VI used to run PI-FF control Simulation on Coupled Tanks system in configuration #2.

**IMPORTANT:** Before you can conduct these simulations, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 5 to configure the lab files first.

Follow this procedure:

1. In *Coupled Tanks.lvproj*, open *Coupled Tanks- Tank2 Level Control Simulation.vi*. The model implements the system's simulation Proportional-plus-Integral (PI) closed-loop with feedforward action, as studied in Section 4.1.2. As mentioned in the pre-lab assignments, the tank 2 water level control loop is based on tank 1 level controller, as developed and tuned in the previous sections. The level controller diagram for the Coupled-Tank in configuration #2 also interfaces directly with your Coupled-Tank hardware. To familiarize yourself with the diagram, it is suggested that you open the model subsystems to get a better idea of their composing blocks as well as take note of the I/O connections.

2. To generate a square wave that goes between 14 and 16 cm for the tank 2 level reference, go to the *Amplitude Command (cm)* section and set the controls to the following:
  - Amplitude = 1 cm
  - Frequency = 0.02 Hz
  - Offset = 15 cm

The total level setpoint for tank 2 should result to be a square wave of  $\pm 1$ cm around the desired equilibrium level  $L_{20}$

3. Enter the proportional, integral, and feedforward control gains found in Section 4.2 in the  $kp\_2$ ,  $ki\_2$ , and  $kff\_2$  controls in the *Control Parameters* section on the front panel. Keep in the the PI-plus-feedforward controller gains for tank 1 of the Coupled-Tank system in configuration #1, as previously implemented. Those are  $kp\_1$ ,  $ki\_1$ , and  $kff\_1$  controls in the *Control Parameters* section on the front panel. Have your lab assistant check your values.
4. Run the VI.
5. The VI should start the Coupled Tanks simulation filling tank1 and tank 2 up to their operating levels  $L_{10}$  and  $L_{20}$ , respectively. Then after a 35-second settling delay (in order to stabilize the system at its operating point), the water level in tank 2 should start tracking the desired  $\pm 1$ cm square wave setpoint around the desired operating level  $L_{20}$ . The corresponding commanded pump voltage, which is proportional to the control effort spent, can also be monitored and plotted on-line.
6. Attach plots showing the *Implemented Tank 2 Level Control* response and the input voltage.
7. Assess the actual performance of the level response and compare it to the design requirements. Measure your response actual percent overshoot and settling time. Are the design specifications satisfied? Explain. If your level response does not meet the desired design specifications, review your PI-plus-Feedforward gain calculations and/or alter the closed-loop pole locations until they do. If you are still unable to achieve the required performance level, ask your lab instructor for advice. Does the response satisfy the specifications given in Section 2.1.4?

**Hint:** Use the graph cursors in the *Measure* tab to take measurements.

### 4.3.3 Tank 2 Level Control Implementation

#### Experimental Setup

The *Coupled Tanks Tank2 Level Control* VI shown in Figure 4.3 is used to perform tank 2 level control exercises in this laboratory. This VI interfaces with the pump and pressure sensors of the Coupled Tanks system. It should be noted that two simple low-pass filters cut-off frequency 2.5 Hz are added to the output signal of the tank 1 and tank 2 level pressure sensors. These filters are necessary to attenuate the high-frequency noise content of the level measurements. Such a measurement noise is mostly created by the sensors environment made of turbulent flow and circulating air bubbles. Although introducing a short delay in the signals, low-pass filtering allows for higher controller gains in the closed-loop system, and therefore for higher performance. Moreover, as a safety watchdog, the controller will stop if the water level in either tank 1 or tank 2 goes beyond 27cm.

**IMPORTANT:** Before you can conduct these experiments, you need to make sure that the lab files are configured according to your setup. If they have not been configured already, then you need to go to Section 5 to configure the lab files first.

Follow this procedure:

1. In *Coupled Tanks.lvproj*, open *Coupled Tanks Tank2 Level Control.vi*. The model implements the system's actual Proportional-plus-Integral (PI) closed-loop with feedforward action, as studied in Assignment #3. To familiarize yourself with the diagram, it is suggested that you open the model subsystems to get a better idea of their composing blocks as well as take note of the I/O connections.

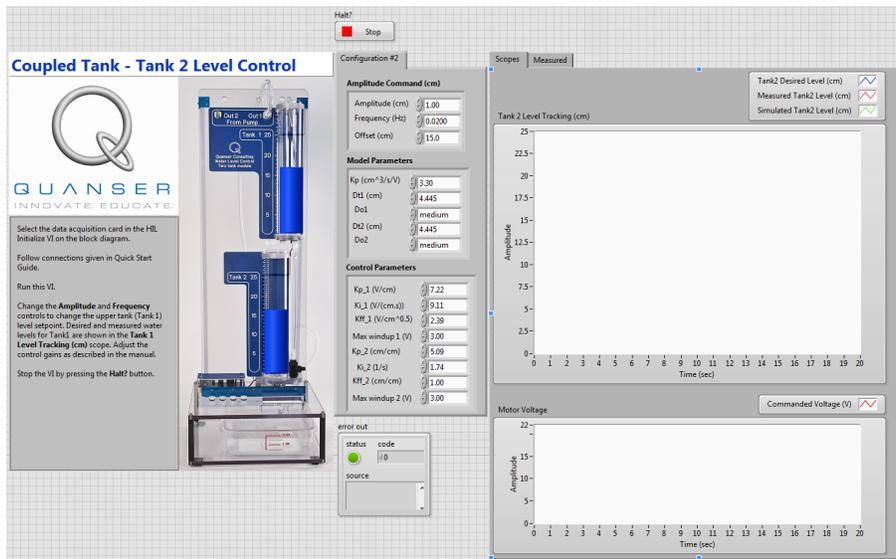


Figure 4.3: VI used to run PI-FF control on Coupled Tanks system in configuration #2.

- To generate a square wave that goes between 14 and 16 cm for the tank 2 level reference, go to the *Amplitude Command (cm)* section and set the controls to the following:

- Amplitude = 1 cm
- Frequency = 0.02 Hz
- Offset = 15 cm

The total level setpoint for tank 2 should result to be a square wave of  $\pm 1$ cm around the desired equilibrium level  $L_{20}$

- Enter the proportional, integral, and feedforward control gains found in Section 4.2 in the  $kp\_2$ ,  $ki\_2$ , and  $kff\_2$  controls in the *Control Parameters* section on the front panel. Keep in the the PI-plus-feedforward controller gains for tank 1 of the Coupled-Tank system in configuration #1, as previously implemented. Those are  $kp\_1$ ,  $ki\_1$ , and  $kff\_1$  controls in the *Control Parameters* section on the front panel. Have your lab assistant check your values.
- Run the VI.
- The VI should start the gear pump thrusting water filling tank1 and tank 2 up to their operating levels  $L_{20}$ . Then after a 35-second settling delay (in order to stabilize the system at its operating point), the water level in tank 2 should start tracking the desired  $\pm 1$ cm square wave setpoint around the desired operating level  $L_{20}$ . The corresponding commanded pump voltage, which is proportional to the control effort spent, can also be monitored and plotted on-line.
- Attach plots showing the *Implemented Tank 2 Level Control* response and the input voltage.
- Assess the actual performance of the level response and compare it to the design requirements. Measure your response actual percent overshoot and settling time. Are the design specifications satisfied? Explain. If your level response does not meet the desired design specifications, review your PI-plus-Feedforward gain calculations and/or alter the closed-loop pole locations until they do. If you are still unable to achieve the required performance level, ask your lab instructor for advice. Does the response satisfy the specifications given in Section 2.1.4?

**Hint:** Use the graph cursors in the *Measure* tab to take measurements.

- Specifically discuss in your lab report the following points:

- How does your actual tank 2 level compare to the simulated response?

- From the plot of the actual level response, measure your system settling time and percentage overshoot. Are the values in agreement with the design specifications? If not exactly, find some of the possible reasons.
- Include in your lab report your final values for  $K_{p\_2}$ ,  $K_{i\_2}$ , and  $K_{ff\_2}$  as well as the resulting response plot of the actual and theoretical  $L_2$  versus  $L_{r\_2}$ . Also include from the same run the corresponding plot of  $V_p$ . Ensure to properly document all your results and observations before moving on to the next section.
- You can now proceed to the next section, which deals with the actual implementation of your PI-plus-Feedforward level controller for tank 2 of the Coupled-Tank system in configuration #2.

## 4.4 Results

Fill out Table 4.1 with your answers from your control lab results - both simulation and implementation.

Description	Symbol	Value	Units
<b>Pre Lab Questions</b>			
<i>Tank 2 Control Gains</i>			
Feed Forward Control Gain	$K_{ff2}$		cm/cm
Proportional Control Gain	$k_{p2}$		cm/cm
Integral Control Gain	$k_{i2}$		1/(s)
<b>Tank 2 Control Simulation</b>			
Steady-state error	$e_{ss}$		cm
Settling time	$t_{s2}$		s
Percent overshoot	$PO_2$		%
<b>Tank 2 Control Implementation</b>			
Steady-state error	$e_{ss}$		cm
Settling time	$t_{s2}$		s
Percent overshoot	$PO_2$		%

Table 4.1: Results

# 5 SYSTEM REQUIREMENTS

## Required Software

Make sure **LabVIEW™** is installed with the following required add-ons:

1. **LabVIEW™**
2. NI-DAQmx
3. NI **LabVIEW™** Control Design and Simulation Module
4. **Quanser Rapid Control Prototyping Toolkit®**

**Note:** Make sure the Quanser Rapid Control Prototyping (RCP) Toolkit is installed after LabVIEW. See the RCP Toolkit Quick Start Guide for more information.

## Required Hardware

- Data acquisition (DAQ) device that is compatible with **Quanser Rapid Control Prototyping Toolkit®**. This includes Quanser DAQ boards such as Q2-USB, Q8-USB, QPID, and QPIDe and some National Instruments DAQ devices.
- Quanser Coupled Tanks.
- Quanser VoltPAQ-X1 power amplifier, or equivalent.

## Before Starting Lab

Before you begin this laboratory make sure:

- **LabVIEW™** is installed on your PC.
- DAQ device has been successfully tested (e.g., using the test software in the Quick Start Guide).
- Coupled Tanks and amplifier are connected to your DAQ board as described Reference [2].

## 5.1 Overview of Files

File Name	Description
Coupled Tanks User Manual.pdf	This manual describes the hardware of the Coupled Tanks system and explains how to setup and wire the system for the experiments.
Coupled Tanks Workbook (Student).pdf	This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement controllers for on the Coupled Tanks plant using LabVIEW™.
Coupled Tanks.lvproj	LabVIEW project that contains all the LabVIEW™ Virtual Instrument (VI) files required for running the Quanser Coupled Tanks labs.
Coupled Tanks -Calibration.vi	VI that is used to calibrate the pressure sensor measurements on the Coupled Tanks system.
Coupled Tanks -Tank1 Level Simulation.vi	VI that simulates Tank1 level controller (configuration 1) for the Coupled Tanks system.
Coupled Tanks -Tank2 Level Simulation.vi	VI that simulates Tank2 level controller (configuration 2) for the Coupled Tanks system.
Coupled Tanks -Tank1 Level Control.vi	VI that implements the PI Tank1 level controller (configuration 1) on the Coupled Tanks system using LabVIEW™.
Coupled Tanks -Tank2 Level Control.vi	VI that implements the Tank2 level controller on the Coupled Tanks system using LabVIEW™.

Table 5.1: Files supplied with the Coupled Tanks

## 5.2 Calibrating the pressure sensor measurements

Follow these steps:

1. Load the LabVIEW™ software.
2. Open the LabVIEW Project *COUPLEDTANK.lvproj*.
3. Open the LabVIEW VI called *Coupled Tanks- Calibration*.
4. Follow the steps in the VI to calibrate both pressure sensors. The sensors should measure about 0V when empty and about 4.1V when filled up to 25cm.

## 5.3 Setup for Tank 1 Level Control Simulation

Follow these steps:

1. Load the LabVIEW™ software.
2. Open the LabVIEW Project *COUPLEDTANK.lvproj*.
3. Open the LabVIEW VI called *Coupled Tanks- Tank 1 Control Simulation*, shown in Figure 3.4.
4. Ensure the PI-FF control gains the  $kp_1$ ,  $ki_1$ , and  $kff_1$  on the VI front panel are set to the value found in the Pre-Lab Questions in Section 3.2.

## 5.4 Setup for Tank 1 Level Control

Follow these steps to get the system ready for this lab:

1. Setup the Coupled Tanks as detailed in the Coupled Tanks User Manual ([2]).
2. If using the VoltPAQ-X1, **make sure the Gain switch is set to 3.**
3. Open *COUPLEDTANK.lvproj* project as outlined in Section 5.3.
4. Open *Coupled Tanks- Tank1 Level Control.vi* shown in Figure 3.5.
5. As discussed in Section 5.3, set the PI gains according to the Pre-Lab Exercise values.
6. **Configure DAQ:** Ensure the HIL Initialize block is configured for the DAQ device that is installed in your system. To do this, go to the block diagram (CTRL-E) and double click on the **HIL Initialize Express VI** shown in Figure 5.1.

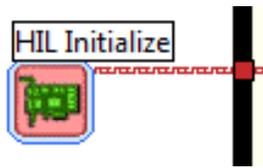


Figure 5.1: HIL Initialize Express VI

7. Under the Main tab, select the data acquisition device that is installed on your system in the *Board type* section. For example, in Figure 5.2 the Q2-USB is chosen.

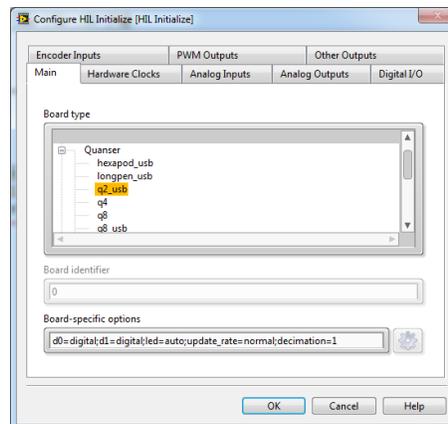


Figure 5.2: Select DAQ board that will be used to control system

## 5.5 Setup for Tank 2 Level Control Simulation

Follow these steps:

1. Load **LabVIEW™** and open *COUPLEDTANK.lvproj*.
2. Open the *Coupled Tanks- Tank2 Level Control Simulation VI*, shown in Figure 4.2.
3. Make sure the control gains are set to the values found in Section 4.2.
4. Ensure the PI-FF control gains the  $k_p_2$ ,  $k_i_2$ , and  $k_{ff_2}$  on the VI front panel are set to the value found in the Pre-Lab Questions in Section 4.2.

## 5.6 Setup for Tank 2 Level Control

Follow these steps to get the system ready for this lab:

1. Go through step 1-4 in Section 5.4 to setup the Coupled Tankssystem and open *COUPLEDTANK.lvproj*.
2. Open *Coupled Tanks-Tank 2 Level Control.vi* shown in Figure 4.3.
3. Make sure the control gains are set as dictated in Section 5.5.
4. **Configure DAQ:** Ensure the HIL Initialize Express VI is configured as explained in Section 5.4.

# 6 LAB REPORT

This laboratory contains two groups of experiments, namely,

1. Tank 1 Level control, and
2. Tank 2 Level control.

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 6.3 you can find some basic tips for the *format* of your report.

## 6.1 Template for Tank 1 Level Control Report

### I. PROCEDURE

#### 1. *Simulation*

- Briefly describe the main goal of the simulation.
- Briefly describe the simulation procedure in Step 6 in Section 3.3.2.

#### 2. *Implementation*

- Briefly describe the main goal of this experiment.
- Briefly describe the experimental procedure in Step 5 in Section 3.3.3.

### II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 6 in Section 3.3.2, *Tank1 level control simulation*.
2. Response plot from step 5 in Section 3.3.3, *Tank 1 level control implementation*.
3. Provide applicable data collected in this laboratory (from Table 3.1).

### III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 7 in Section 3.3.2.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 6 in Section 3.3.3.

### IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in Step 7 in Section 3.3.2, *Tank1 level control simulation*.
2. Whether the controller meets the specifications in Step 6 in Section 3.3.3, *Tank1 level control implementation*.

## 6.2 Template for Tank 2 Level Control Report

### I. PROCEDURE

#### 1. *Simulation*

- Briefly describe the main goal of the simulation.
- Briefly describe the simulation procedure in Step 6 in Section 4.3.2.

#### 2. *Implementation*

- Briefly describe the main goal of this experiment.
- Briefly describe the experimental procedure in Step 6 in Section 4.3.3.

### II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 6 in Section 4.3.2, *Tank2 level control simulation*.
2. Response plot from step 6 in Section 4.3.3, *Tank2 level control implementation*.
3. Provide applicable data collected in this laboratory (from Table 4.1).

### III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Peak time, percent overshoot, steady-state error, and input voltage in Step 7 in Section 4.3.2.
2. Peak time, percent overshoot, steady-state error, and input voltage in Step 7 in Section 4.3.3.

### IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in Step 7 in Section 4.3.3, *Tank2 level control implementation*.

## 6.3 Tips for Report Format

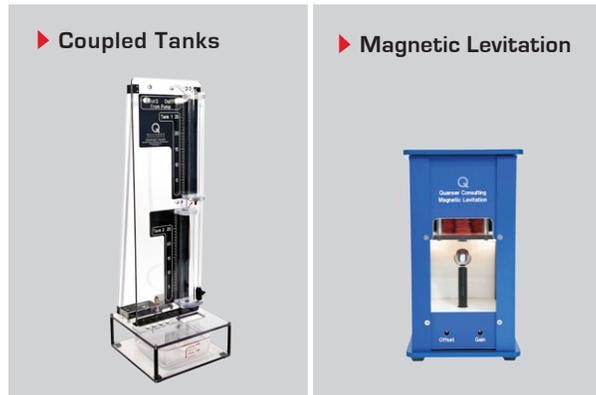
### PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

# REFERENCES

[1] Quanser Inc. *Coupled Tank User Manual*, 2012.

## Process control plants for teaching and research



These plants are ideal for intermediate level teaching. They are also suitable for research relating to traditional or modern control applications of process control. For more information please contact [info@quanser.com](mailto:info@quanser.com)

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