OBJECTIVES: Before embarking on this hands-on session, you should have been introduced to the concepts of feedforward and cascade control systems in the lectures. This hands-on session is formulated to consolidate your understanding of the topics via practice on a simulated system. No separate report needs to be submitted for this exercise. However, it is important for you to complete the entire session, as concepts pertaining to a practical course like EE3302/TE3302 are best grasped through hands-on practice.

BACKGROUND: Feedforward (FF) and cascade control are common forms of advanced control systems used when a better control performance is desired, especially when there exists significant disturbances to the process which upset the process variable under control. While in some cases, the upset is tolerable, in many others, they cause problems to the overall production/operational system. In general, the control system dislikes disturbances and we would like to be able to minimise the effects of these disturbances.

The FF control system requires a model of the process and a model of the disturbance. It also requires that the disturbance signal must be measurable. Then, via a FF controller (which uses both the model of the process and the disturbance), a FF signal is deliberately constructed to cancel out the disturbance signal so that minimal upset is caused. However, in practice, no model is perfect and since FF control is based on the models, there will be residual effects arising from any modelling errors. The residual effects are usually handled via an additional feedback (FB) controller.

In a cascade control system, the output of one feedback (FB) controller (the “primary”) provides the set point to a second feedback (FB) controller (the “secondary”). For cascade control to work well, the inner loop should be faster compared to the outer loop. Then any disturbance arising in the inner loop can be adequately quenched by the secondary controller before it affects the outer loop. Thus, from the same reasoning, the cascade control arrangement does not help much if disturbances enter the system via the primary loop instead.

This exercise will attempt to reinforce these key concepts. At the end of it, you will also gain some experience in using LabVIEW.
PART I: FEEDFORWARD CONTROL SYSTEMS

The process considered is a water heating process as shown in Figure 1. The process variable \((y)\) to be controlled is the outlet temperature. The process variable is controlled by varying the amount of heating via the fuel flow rate \((u)\) (the manipulated variable). The flow rate of the water entering the tank can vary, depending on factors such as the demand for water from other processes, water supply pressure etc. This variation of the flow \((w)\) constitutes a load disturbance to the heating process. We will refer to signal \(w\) (disturbance) as the “LOAD” in the rest of the manual.

![Figure 1: PROCESS HEATER](image)

The process can be depicted in the block diagram form as shown in Figure 2. The transfer function \(G_W(s)\) represents the dynamic relation between the load \((w)\) and outlet temperature \((y)\), (i.e., the disturbance model). The transfer function \(G_P(s)\) represents the dynamic relation between fuel flow \((u)\) and outlet temperature \((y)\), (i.e., the process model).
In the FF control strategy, FF control is usually augmented with FB control. Figure 3 shows the overall FF/FB control scheme to be used in the simulation here.

The switches are provided for you to experiment with different combination of control modes (e.g. with and without disturbance, with and without FF etc.), as necessary when we proceed with the simulation.

Note that the dynamics of the actual heating process is already pre-set for you in this simulation study. Thus, you do not know the model for the process at the outset. This is exactly the situation when you are faced with a real practical system; you will not be given its transfer function!
I.1. RUNNING THE PROGRAM

Step 1: Start **Windows 95 or higher**.
Step 2: If you are running from the designated PC in the laboratory:
   Go to directory “c:\ee3302\feedforward”.
   Open the file “main-feedforward.vi”.

If you are running from a remote PC on NUSNET:
   Map network drive L: \mchlab\NI .
   Run L:\LabVIEW\labview.exe
   Open the file “main-feedforward.vi” from L:\LabVIEW\labexperiment.

I.2. CONTROL PANEL

After the initial title display and loading of the associated library files in LabVIEW, the control panel for the FF control strategy will be presented (Figure 4).

![Figure 4: CONTROL PANEL](image-url)
The panel is quite typical of what you can expect to see on a real industrial controller, except for the “Load” part. You can choose to turn off or turn on the load disturbance in this simulation study, or vary its amplitude. This is necessary to let you explore the performance of FF control under the influence of different amplitudes of disturbances. In practice, however, you have to live with disturbances most of the time. You cannot simply switch it off!

There are four main sections in the panel. For tuning purposes, the parameters for the FB and the FF controller are displayed, and you can vary these parameters. (For the moment, you do not have to worry about what to enter for each of these boxes yet). The set point \( r \) and the load \( w \) can also be altered in the bottom left hand corner of the panel.

To enable FB control, click once on the \textit{FB control} button (Auto mode). Clicking another time on the same button disables it (Manual mode). To select FF control, click once on the \textit{FF control} button (ON mode). Clicking another time on the same button disables it (OFF mode). In a similar manner, to select load (disturbance), click once on the \textit{Load Select control} button (ON mode). Clicking another time on the \textit{Load Select control} button disables it (OFF mode). The \textit{Bypass FF} button allows the Load signal to be directly input to \( G_p \), as shown in Figure 3, thus allowing the step tests in Section I.3 to be done. Clicking once on this button turns ON the Bypass mode (YES to bypass). Clicking a second time turns OFF the Bypass mode (NO to bypass).

In the FB Controller parameters section, the gains for the PID controller can be entered. In the FF Controller parameters section, the coefficients of the transfer function for the FF controller can be entered. The output section of the panel shows the process variable \( y \). To run the simulation, simply click on the “RUN” button in the top toolbar.

\section*{I.3. MODELLING FROM STEP TESTS}

To use and commission the FF controller, we will need to have a model of the process and a model of the disturbance. (In paper-pen tutorials, usually the model is given to you. In practice, you have to work to get them). Here, for both the process and disturbance models, we use a first order transfer function model given by:

\[
\frac{Y(s)}{U(s)} = \frac{K_p}{1 + s \tau_p}
\]

where \( Y(s) \) and \( U(s) \) are the transforms of the output and the input signals of the process respectively. The values of \( K_p \) and \( \tau_p \) can be extracted from the step
response as shown in Figure 5. Note that in this experiment, we do not consider any delay in the response of the system, but in practice this is not so.

![Figure 5: PARAMETER ESTIMATION FROM STEP TEST](image)

No prize for the correct guess. We are now going to carry out the step tests.

We will obtain the model for the disturbance first, i.e. the relationship between \( y \) and \( w \). Make sure that the FF controller is OFF, Load Select is ON, Bypass is OFF (NO to bypass) and that FB control is put in the Manual mode.

Increase the load (\(w\)) by 50\% (i.e., enter the value of 0.5 for the Load). (this is equivalent to having a step change at the input of \(G_W(s)\)). After the above mentioned settings have been made, run the simulation by clicking on the button on the top toolbar.

Observe the dynamic effect on the process variable (\(y\)). Extract the gain, deadtime and time constant accordingly from the step response.

To obtain a more accurate value for the time constant, right click with the mouse pointer on the graph area. Select X-Scale\(\rightarrow\)Marker Spacing\(\rightarrow\)Uniform. Also, select X-Scale\(\rightarrow\)Formating to ensure that the setting is as shown in Figure 6. Do the same for the Y-scale.
Change in load ($\Delta w$):

Change in process variable ($\Delta y$):

Gain $K_p$:

Time constant ($\tau_p$):

Thus, produce the transfer function model of the disturbance.

$$G_W(s) =$$

Next, we will work on the model for the process, i.e., the relationship between $u$ and $y$. Ensure that the FF controller is OFF, Load Select is OFF, Bypass is On (YES to bypass) and FB control is put in the Manual mode.

Enter the load ($w$) to 0.5. This will create a step change in the input ($u$) for $G_p(s)$. Observe the dynamic effect on the process variable ($y$). Record the following:

Change in load ($\Delta u$):

Change in measurement ($\Delta y$):

Process gain ($K_p$):
Time constant ($\tau_p$): 

Thus, produce the transfer function model of the process:

$$G_p(s) =$$

### I.4. COMMISSIONING THE FEEDFORWARD CONTROLLER

With the models available, we can now commission the feedforward controller.

$$G_{FF}(s) = \frac{G_w(s)}{G_p(s)} =$$

If you are wondering why this is so, it is time to relook at your lecture notes.

Express the transfer function in the standard polynomial form:

$$\frac{a_n s^n + a_{n-1} s^{n-1} + ... + a_0}{b_n s^n + b_{n-1} s^{n-1} + ... + b_0}.$$

The design of the FF controller is completed. You may now enter the coefficients of the polynomials on the numerator and the denominator of the FF transfer function into the control panel. Figure 7 illustrates how this is done.

$$H(s) = 4.67s + 2.70$$
We are ready to run the simulation and will assess the performance with (1) FF only, (2) FF and FB, (3) Non-ideal FF with FB.

I.4.1. FF Controller Only

We will first run the simulation for FF control only (no FB control). Thus, we will continue to leave the FB portion of the controller in the Manual mode.

We will introduce a load change and see how the FF controller responds to the change. We hope to see no change in the process variable (y) as before the load change happens.

Re-open the file “main-feedforward.vi”. Input a value of zero for the load. Ensure that the FF controller is ON, Load Select is ON, Bypass is OFF (NO) and FB control is set to Manual. Run the simulation. After some time, input a value of 0.6 for the load to initiate a load change (change of process flow rate).

Is there any discernible change in y after the load is introduced?

If so, then the feedforward controller needs fine tuning. Fine tune your FF controller if necessary. Record your final tuning values, and repeat the above mentioned step (i.e., re-run the simulation and add in the load disturbance). Note the final response after the fine tuning.

Maximum deviation of y after fine tuning:

In practice, there will be a law of diminishing returns. At some point, the cost of additional process testing will outweigh the potential benefits of improved feedforward controller tuning. At that point, the reasonable approach is to say “we’ve tuned the feedforward controller good enough.”
I.4.2. FF with FB Control

Now, we will use both the FF and the FB controller. For the FB controller, a PI controller is used. The PI controller has two parameters, the proportional gain and the integral gain (reset). You may use the suggested values below:

Gain: 1
Reset: 0.25

Re-open the file “main-feedforward.vi”. Enter these values for the FB controller, then put it in the Auto mode. Enter a setpoint of 0.5. Make sure the load select is OFF, the FF controller is ON, NO to Bypass Feedforward, and FB control is set to Auto mode. Run the simulation.

What is the steady state error? 

After some time, add in a load disturbance by entering 0.3 for the load and setting load select and FF controller ON. Observe the combined FB-FF controller system output (y). How much of this response do you think is due to:

FF control action
FB control action

If your FF controller is ideally tuned, once the process variable is brought to the set point, essentially all the subsequent control action to deal with disturbances can be attributed to FF control. However, if your FF controller is near to the ideal parameters. A small portion of the disturbance is still taken care of by your FB controller.

I.4.3. Non-Ideal FF with FB Control

In the last section, we have essentially used an ideal FF control with FB control. We have also seen that if the FF control is perfect, then FB control is not really necessary for load disturbance attenuation. However, such a situation is probably not realistic, since a perfect FF controller will be based on perfect models, and we will never be able to obtain perfect models.
To simulate this more likely scenario, we will change the process model, so that the FF control is no longer ideal.

Open the file “main-feedforward1.vi”.

We will continue to use the present FF controller, although it is now non-ideal for the new process model. Now, FF control alone will not fully correct the disturbance, the balance will have to be compensated by the FB control action.

First observe FB control alone. Put the FB controller in Auto mode (with the P and I gain similar to the previous section) but with the FF control OFF, Bypass OFF and the load select ON. Enter a zero value for the load. Run the simulation. After some time, add in a load disturbance of 0.4. Observe the response.

Maximum deviation of $y$: ________  
Steady state error: ________

Next, observe FF control alone. Re-open the file “main-feedforward1.vi”. Put the FB controller in Manual mode, with FF control ON, Bypass OFF and Load Select ON. Make sure that the load has a zero value and the FF controller has the same values as in the previous section. Run the simulation. After a while, add in a load disturbance of 0.4. Observe the response.

Maximum deviation of $y$: ________

Finally, observe FB with FF control. Re-open the file “main-feedforward1.vi”. Put the FB controller in Auto mode, with FF control ON, Bypass OFF and Load Select ON. Enter a load disturbance of zero value and a setpoint value of 0.4. Remember to enter the the parameters of the feedforward controller similar to the previous section. Run the simulation and after some time add in a load disturbance of 0.4.

Maximum deviation of $y$: ________

You should observe that with an ideal FF, FB is only needed if set point tracking is necessary. FB is not needed for disturbance attenuation. However, if the FF control is non-ideal, FB control is needed for both disturbance attenuation and set point tracking.
PART II: CASCADE CONTROL SYSTEMS

The water heating process of Figure 1 is still considered in this part. However, now we consider that the fuel supply pressure is no longer a constant. A secondary loop devoted to the control of the flow rate of fuel is considered, setting the stage for a cascade control system (Figure 8). We will not consider any further disturbances in the water flow rate which has been addressed in PART I.

An equivalent block diagram is shown in Figure 9. \( y \) and \( u \) are the process variables of the primary and secondary loop respectively. \( w_1 \) is the load disturbance entering the primary loop and \( w_2 \) is the load disturbance entering the secondary loop.
II. 1.  RUNNING THE PROGRAM

Step 1:  Start Windows 95 or higher.
Step 2:  If you are running from the designated PC in the laboratory:
         Go to directory “c:\lee3302\cascade\”.
         Open the file “main-cascade.vi”.

         If you are running from a remote PC on NUSNET:
         Map network drive L: \mchlab\NI.
         Run L:\LabVIEW\labview.exe
         Open the file “main-cascade.vi” from L:\LabVIEW\labexperiment.

II. 2.  CONTROL PANEL

After the title display and loading of the associated library files in LabVIEW, the control panel for the cascade control strategy is presented (Figure 10).

In this panel, there are four main sections. For tuning purposes, the parameters for the primary loop controller and that for the secondary loop controller are displayed in the primary loop section and the secondary loop section respectively (The primary loop section and the secondary loop section are on the left side of the front panel). The values for the Proportional (P), Integral (I) and Derivative (D) controllers can be changed in these two sections. The set point and the load disturbance can be also be altered in the bottom left hand corner of the panel. The output section of the panel plots the process variables of the primary loop and the secondary loop.

Figure 9: EQUIVALENT BLOCK DIAGRAM FOR THE CASCADE CONTROL SYSTEM
II. 2. TUNING THE CONTROLLERS

In the control panel, the default configuration is cascade control configuration, with two loops, primary and secondary, both on automatic. Disturbances (load upsets) can be introduced separately into either the secondary loop or primary loop. Referring to Figure 10, the value for Load 1 refers to the disturbance \( w_1 \) introduced to the primary loop and the value for Load 2 refers to the disturbance \( w_2 \) introduced to the secondary loop.

Click to set cascade control on. For the primary loop parameters, enter a P gain of 3, I gain of 3.75, D gain of zero; for the secondary loop parameters, enter a P gain of 1.5, I gain of 1.1, D gain of zero. Start the operation by clicking on the “RUN” button in the top toolbar. After a while, increase the set point by 40%, i.e., change the set point by keying in 0.4 in the box.

Observe the secondary loop response:

Is it approximately quarter-decay? ____________

(By quarter-decay, it means that the peak of the second overshoot to first is around 1:4. It is common to tune a controller to “quarter-decay”)
Period of oscillation _______ (oscillation amplitude should be decreasing)

Amount of overshoot _______

Rise time _______

You can use any tuning rules to adjust the PID parameters (e.g. Ziegler-Nichols). Here, we will give a good set to you to achieve “quarter-decay”. Enter the following tuning values for the secondary loop controller:

Gain (P): 1.50
Reset (I): 1.36
Derivative (D): 0.00

Enter the following tuning values for the Primary controller:

Gain (P): 2.50
Reset (I): 1.00
Derivative (D): 0.0

Start the operation of the front panel. Change the set point to 0.4. Observe the primary loop response:

Is it approximately quarter-decay? _______

Period of oscillation: _______

Amount of overshoot _______

Rise time _______

Steady-state error ($y$) _______
The cascade control system is tuned. In the next section, we will assess the performance of cascade control, when disturbances arise.

II.3. PERFORMANCE

In order to see the advantages of cascade control, we will compare the performance of a cascade control system to that of a single-loop control system.

II.3.1 Cascade Control

Use the control parameters for the primary and secondary loops as in the previous section. When the signals have stabilised, read and record the values for the following variables:

Set point: ___________
Primary PV, y: ___________
Secondary controller output, v: ___________

In order to have a better display of the process response in the following sections, you may want to zoom the PV scale to 50% - 60%.

To initiate a load change in the primary loop, change the value of Load 1 to 0.2.

Observe the response of the primary PV (y):

Maximum deviation from set point: ___________
Does the primary PV (y) eventually return to set point? ___________
Secondary controller output, v: ___________

You have just observed the response to a load change in the outer loop. To compensate for this, the primary controller increased the demand on the inner loop; i.e., it changes the set point of the secondary controller. To meet this additional demand, the secondary controller output also changes.

Change the value of Load 1 to its original value.
When the control loops have stabilised, initiate a disturbance to the secondary loop by changing the value of Load 2 to 0.2.

Observe the response and record the following:

Maximum deviation from set point of primary PV (y): 

Does the primary PV eventually return to set point? 

Secondary controller output after inner loop load change:

You have just observed the response to a load change on the inner loop. Since the load on the outer loop has not changed, the long term demand of the primary controller on the inner loop (i.e., the set point of the secondary controller) does not change although it may undergo some fluctuation in the short term. But to compensate for the changed load on the inner loop, the secondary controller output has to change.

The most significant observation is that the secondary process load change is contained within the inner loop. The effect on the primary process variable is fairly small.

Before going on, restore the secondary load (Load 2) to its original value.

II.3.2 Single-loop Control

This section of the laboratory exercise will initiate the same type of load changes, but the control structure will be a simple FB controller. The secondary controller will be eliminated, and the primary controller output ($r_2$) will go directly to the valve (v). Click on the cascade ON/OFF button to turn cascade control off, thus having a single-loop control structure.

You have just “softwired” around the secondary controller. The primary controller output now goes directly to the valve. The Secondary Controller is now inactive.

Check that the control parameters remain the same as previously set.

Although the control structure has been altered, the process itself has not. There is still a secondary process which feeds a primary process, with independent load disturbances to each.
Change the load on the primary loop by altering the value of Load 1 to 0.2.

Observe the response and record the following:

Maximum deviation from set point for the primary output: __________

Is this response approximately the same or significantly different from the response with cascade control observed earlier? __________

Observation: With a disturbance to the primary process, the presence or absence of a cascade loop makes very little difference.

Return the primary process load to its original value.

When the control loop is stabilised, initiate a load change to the secondary process by altering the value of Load 2 to 0.2.

Observe and record the following:

Maximum deviation from set point for the primary output: __________

Is the response to this load change approximately the same or significantly different from the response to the same load change with cascade control? __________

Is the response to this load change approximately the same or significantly different from the response to a primary load upset, both without using cascade control? __________

You have observed the responses to load upsets on both the secondary and primary processes, without using a cascade control system. Since there is no inner loop to compensate for the load upset on the secondary process, the responses are
approximately the same. Comparing the response to a secondary load upset both with and without cascade, you should observe that there is a very significant improvement when cascade control is used.