

NATIONAL UNIVERSITY OF SINGAPORE

EE3302/EE3302E Industrial Control Systems

E1: ADVANCED CONTROL SYSTEMS

OBJECTIVES: Before embarking on this hands-on session, you should have been introduced to the concepts of cascade and feedforward control systems in the lectures. This hands-on session is formulated to consolidate your understanding of the topics via practice first on a simulated system, and then on a desktop thermal chamber.

BACKGROUND: Cascade and Feedforward (FF) 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 minimize the effects of these disturbances.

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.

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 modeling errors. The residual effects are usually handled via an additional feedback (FB) controller.

This exercise will attempt to reinforce these key concepts, via first a simulation study followed by an experiment on a thermal chamber apparatus. At the end of this session, you will also gain some experience in using LabVIEW.

PART I: CASCADE 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). A secondary loop devoted to the control of the flow rate of fuel is considered, setting the stage for a cascade control system.

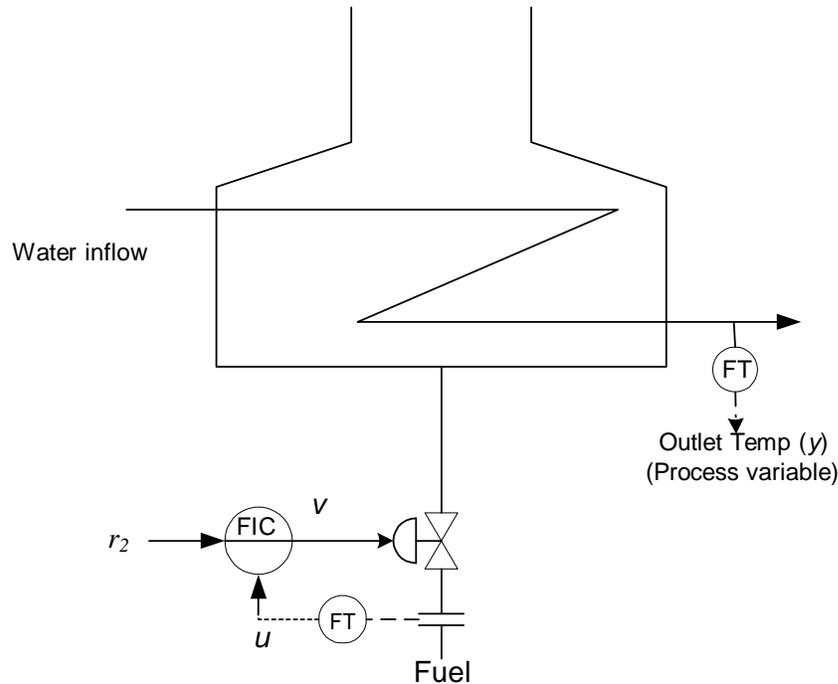


Figure 1: FLOW CONTROL LOOP FOR REGULATING THE FUEL FLOW

An equivalent block diagram is shown in Figure 2. 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.

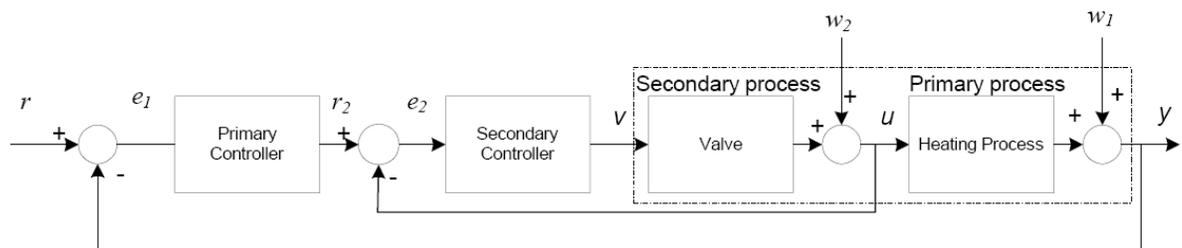


Figure 2: EQUIVALENT BLOCK DIAGRAM FOR THE CASCADE CONTROL SYSTEM

I. 1. RUNNING THE PROGRAM

Go to directory “c:\ee3302\cascade\”.

Open the file “main-cascade.vi”.

I. 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 3).

In this panel, there are 4 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 2 sections. The set point and the load disturbance can also be altered in the bottom left hand corner of the panel. The first graph in the output section of the panel plots the process variables of the primary loop and the secondary loop; the second graph plots the secondary controller output, v.

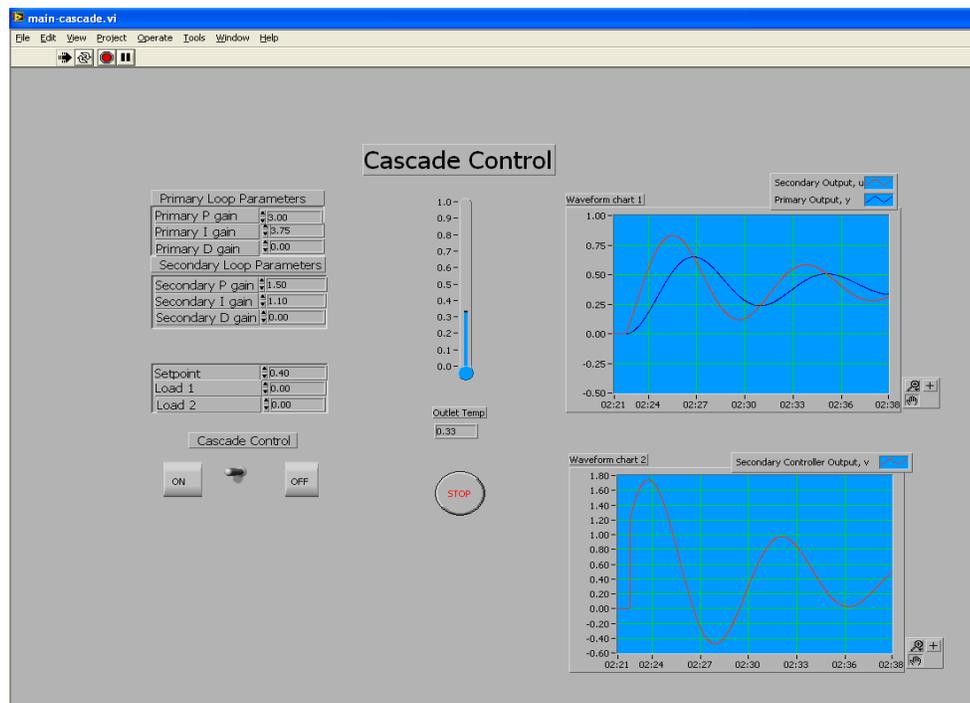


Figure 3: FRONT PANEL FOR CASCADE CONTROL

I. 3. TUNING THE CONTROLLERS

In the control panel, the control configuration can switch between cascade control and single loop control by clicking the “Cascade Control ON/OFF” toggle. Disturbances (load upset) can be introduced separately into either the secondary loop or primary loop. Referring to Figure 3, 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 of the front panel 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 primary 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 _____

Amount of overshoot (in %) _____

Rise time _____

Qn 1: What do you think is the rationale and significance to tune towards a quarter-decay waveform?

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 primary loop controller:

Gain (P):	2.50
Reset (I):	1.00
Derivative (D):	0.00

Enter the following tuning values for the secondary controller:

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

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 (in %) _____

Rise time _____

The cascade control system is tuned. In the next section, we will assess the performance of cascade control, when disturbances arise.

I.4. 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.

I.4.1 Cascade Control

Use the tuned controller parameters for the primary and secondary loops as in the previous section. Run the simulation with a setpoint of 0.4 and, when the signals have stabilized, read and record the values for the following variables:

Set point SP, r : _____

Primary PV, y : _____

Secondary controller output, v : _____

Secondary loop process variable, u : _____

Case 1: Load 1 Disturbance (Cascade Control)

To initiate a load change in the primary loop, change the value of Load 1 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, v: _____

Secondary loop process variable, u: _____

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.

Case 2: Load 2 Disturbance (Cascade Control)

Change the value of Load 1 to its original value.

When the control loops have stabilized, 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: _____

Secondary loop process variable, u: _____

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.

I.4.2 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 toggle to turn cascade control off, thus having a single-loop control structure as shown in figure 4.

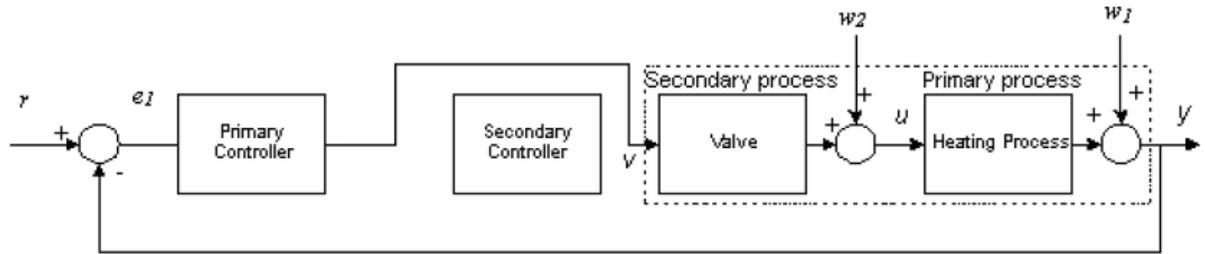


Figure 4: EQUIVALENT BLOCK DIAGRAM FOR THE SINGLE-LOOP CONTROL SYSTEM

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

Case 3: Load 1 Disturbance (Open-loop)

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

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?

Return the primary process load to its original value.

Case 4: Load 2 Disturbance (Open-loop)

When the control loop is stabilized, 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

Qn 2: Based on the four cases above, in which situation is cascaded control most effective? Explain your stance.

PART II: FEEDFORWARD CONTROL SYSTEMS

The process considered is still the water heating process as shown in Figure 5. However, instead of considering the manipulated variable, the flow rate of the water entering the tank, which can vary depending on factors such as the demand for water from other processes, water supply pressure etc, shall be analyzed in this part. This variation of the flow (w) constitutes a load disturbance to the heating process. We will refer to signal w (disturbance) as the “Disturbance” in the rest of the manual.

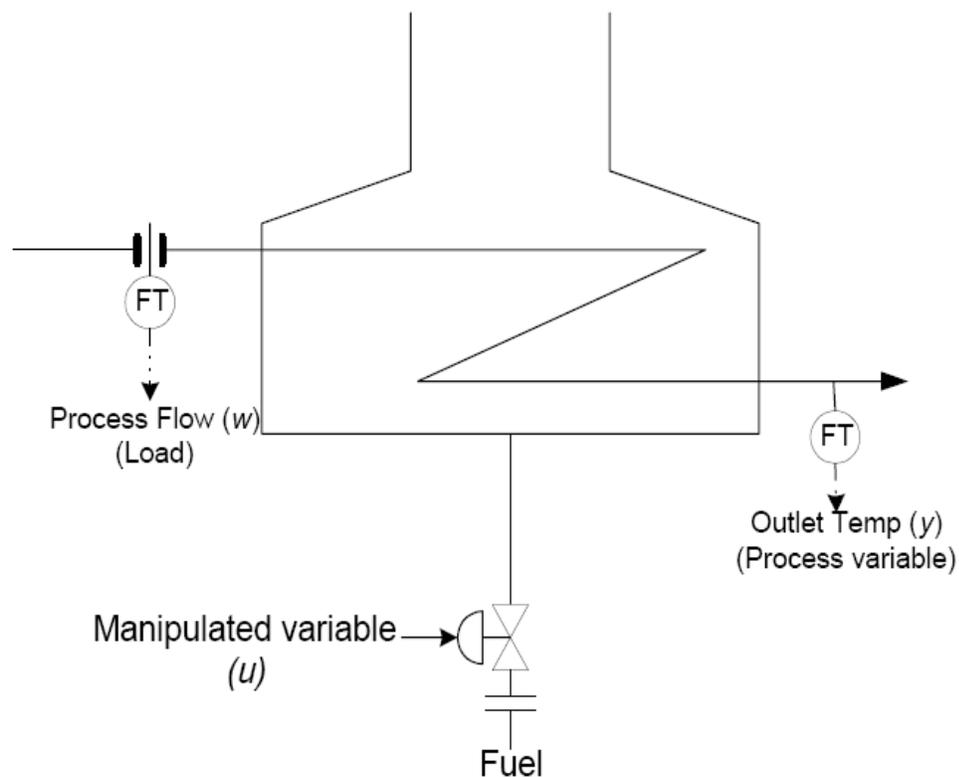


Figure 5: PROCESS HEATER

The process can be depicted in the block diagram form as shown in Figure 6. The transfer function $G_W(s)$ represents the dynamic relation between the disturbance (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).

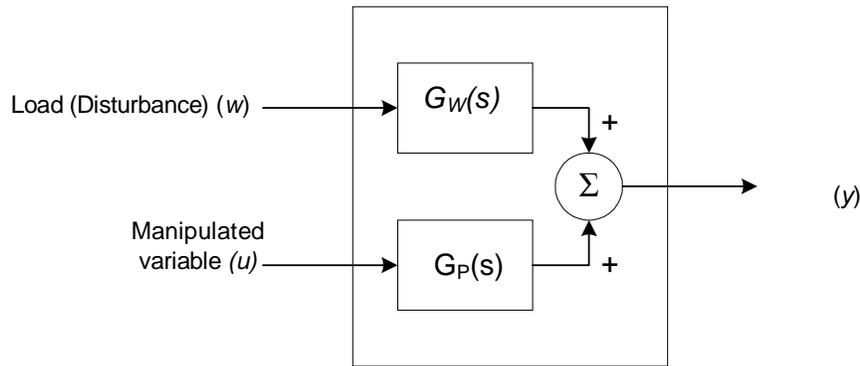


Figure 6 BLOCK DIAGRAM REPRESENTATION

In the FF control strategy, FF control is usually augmented with FB control. Figure 7 shows the overall FF/FB control scheme to be used in the simulation here.

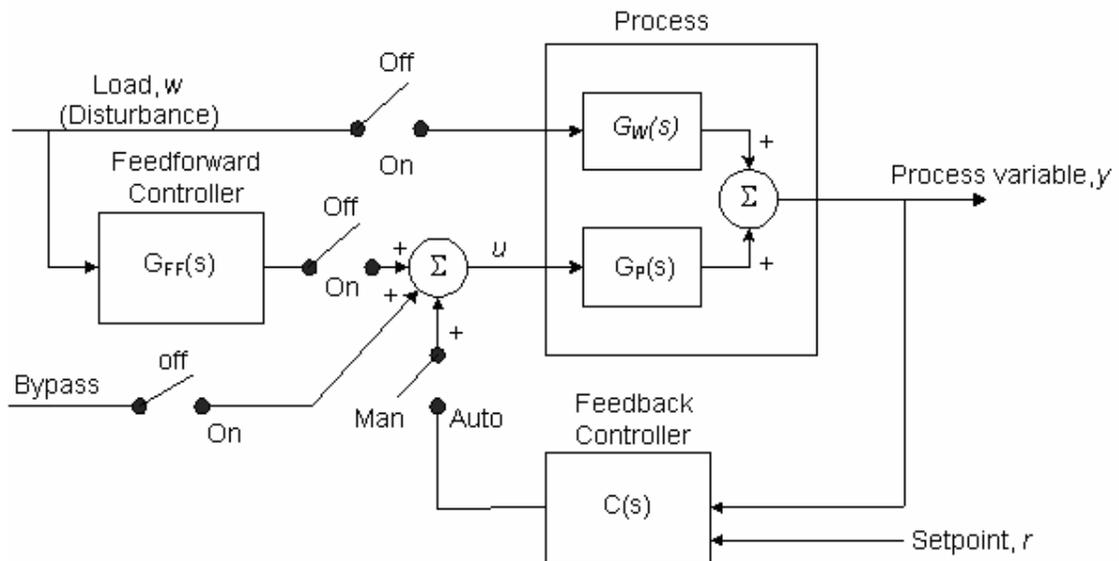


Figure 7 COMBINED FF/FB CONTROL CONFIGURATION

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!

II.1. RUNNING THE PROGRAM

Go to directory “C:\ee3302\feedforward”.

Open the file “main-feedforward.vi”.

II.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 8).

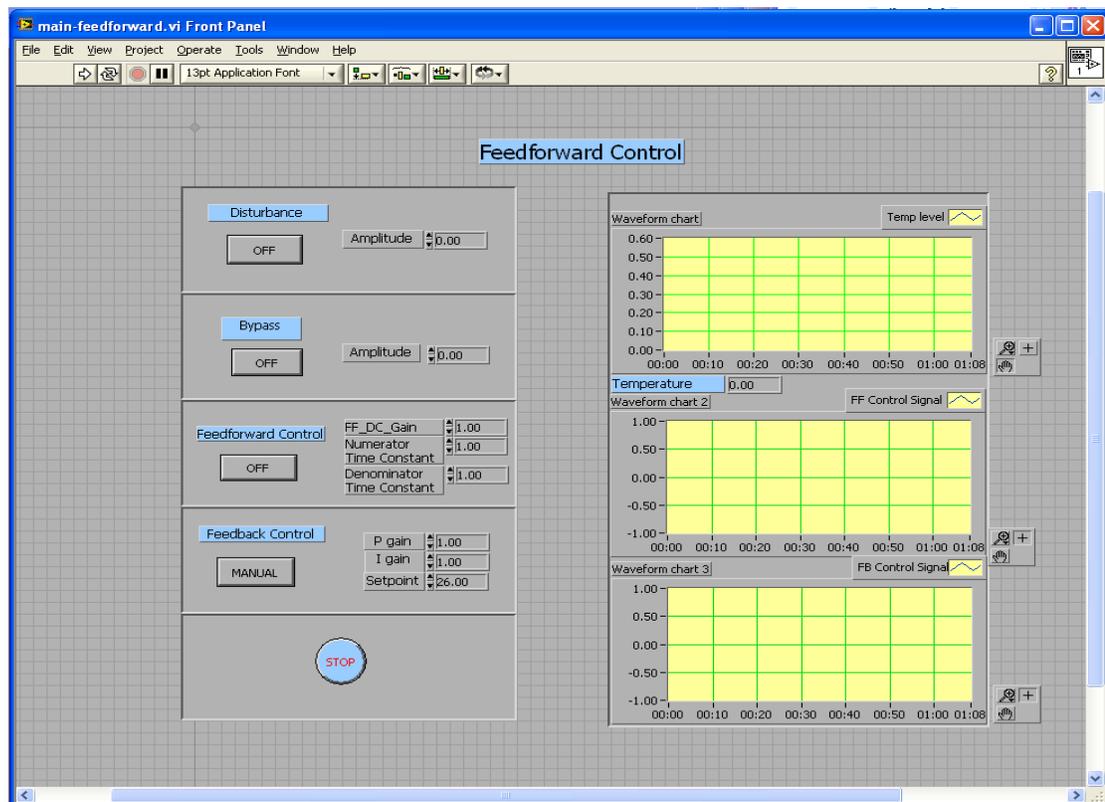


Figure 8: CONTROL PANEL

The panel is quite typical of what you can expect to see on a real industrial controller, except for the “Disturbance” 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 4 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 disturbance (w) can also be altered accordingly.

To enable FB control, click once on the *FB control* button (Auto mode). Clicking another time on the same button disables it (Manual mode). To select FF control, click once on the *FF control* button (ON mode). Clicking another time on the same button disables it (OFF mode). In a similar manner, to select disturbance, click once on the *Disturbance Select control* button (ON mode). Clicking another time on the *Disturbance Select control* button disables it (OFF mode). The *Bypass FF* button allows the Open Loop Control signal to be directly input to G_p , as shown in Figure 7, thus allowing the step tests in Section II.3 to be done. Clicking once on this button turns ON the Bypass mode (ON mode). Clicking a second time turns OFF the Bypass mode (OFF mode).

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.

II.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 as given by:

$$\frac{Y(s)}{U(s)} = \frac{K_p}{u_p} \frac{1}{1 + s\tau_p}$$

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 , u_p and τ_p can be extracted from the step response as shown in Figure 9. Note that in this experiment, we do not consider any delay in the response of the system, but in practice this is not so.

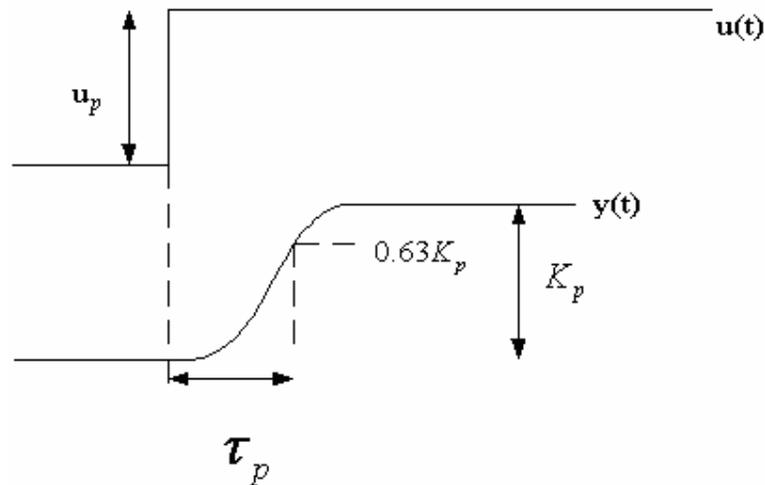


Figure 9: PARAMETER ESTIMATION FROM STEP TEST

We are now going to estimate the process model $G_P(s)$ and the disturbance model $G_W(s)$ with the above-mentioned parameter estimation step test.

Based on Figure 7, activate/de-activate the appropriate switches on the control panel to obtain the open loop response for the disturbance model $G_W(s)$. State the position of the switches you have selected:

Disturbance	<u>ON / OFF</u>
FF Controller	<u>ON / OFF</u>
Bypass	<u>ON / OFF</u>
FB Controller	<u>AUTO / MAN</u>

Now you could run the simulation and after a while you could change the amplitude of Disturbance to apply a step input to the process. Based on the response curve you get, which is similar to Fig. 9, the transfer function model of the disturbance may be approximated by:

$$G_W(s) = \underline{\hspace{10em}}$$

Next, we will work on the model for the process, i.e., the relationship between u and y . Again, based on Figure 7, select the appropriate switches position to obtain the open loop response for the process model $G_P(s)$. State the position of the switches you have selected:

Disturbance	<u> ON / OFF </u>
FF Controller	<u> ON / OFF </u>
Bypass	<u> ON / OFF </u>
FB Controller	<u> AUTO / MAN </u>

You could change the amplitude of Bypass input to apply a step input to the process. Thus, the transfer function model of the process may be approximated by:

$$G_p(s) = \underline{\hspace{10em}}$$

II.4. COMMISSIONING THE FEEDFORWARD CONTROLLER

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

$$G_{FF}(s) = -\frac{G_W(s)}{G_P(s)} = \underline{\hspace{10em}}$$

If you are wondering why this is so, it is time to relook at your lecture notes. Express the transfer function $G_{FF}(s)$ in the following polynomial form:

$$K \frac{a_1s + 1}{b_1s + 1}$$

The design of the FF controller is completed. You may now enter Static gain K and the time constants a_1, b_1 of the numerator and the denominator of the FF transfer function into the control panel. Figure 10 illustrates how this is done by an example.

$$G_{FF}(s) = -2 \frac{8s+1}{10s+1}$$

Feedforward Control

FF_DC_Gain	-2.00
Numerator Time Constant	8.00
Denominator Time Constant	10.00

Figure 10: ENTERING THE FF TRANSFER FUNCTION

Now we are ready to run the simulation and assess the performance with the commissioned FF. Please proceed to section **II.4.1**.

II.4.1. FF Controller

We will introduce a disturbance 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 disturbance change happens.

Input a value of zero for the Disturbance. Ensure that the FF controller is ON, Disturbance Select is ON, Bypass is OFF and FB control is set to *Manual*. Run the simulation. After some time, input a value of 0.6 for the Disturbance to initiate a disturbance change (change of process flow rate).

It should be observed that there are **no** discernible change in y after the disturbance is introduced. We have successfully commissioned the feedforward controller.

PART III: CONTROL OF A DESKTOP THERMAL CHAMBER

Figure 11 shows the setup of the thermal chamber system. In this system, the thermal chamber unit is mounted on a National Instruments SC-2345 platform with configurable connectors. SC-2345 is connected to a DAQ device through a 68-pin shielded cable. The power module SCC-PWR01 is used to supply digital power (+5V) and analog power ($\pm 15V$) to the SCC modules in the SC-2345 carrier. One NI SCC-TC02 J-type thermocouple input module is used as the temperature sensor to measure the air temperature in the chamber. Two SCC-FT01 (Feedthrough Module) are used to control the light and the fan. The power supply on the back of the chamber provides the power for both the light and fan in the chamber, by being routed through either SCC-FT01 (Feedthrough Module) in the SC-2345 and then to the light and fan.

The air temperature can be controlled by adjusting the light and fan. Figure 12 shows the configuration of the chamber unit. Real-time experiments on the unit can be easily implemented by connecting the setup with the DAQ device in the PC. In this system, the controlled variable of interest is the temperature of the chamber of the shaft, with the electrical input to the light acting as the controlling variables. The fan serves as a disturbance source, and you may assume that the input to the fan is a disturbance signal which is measurable.

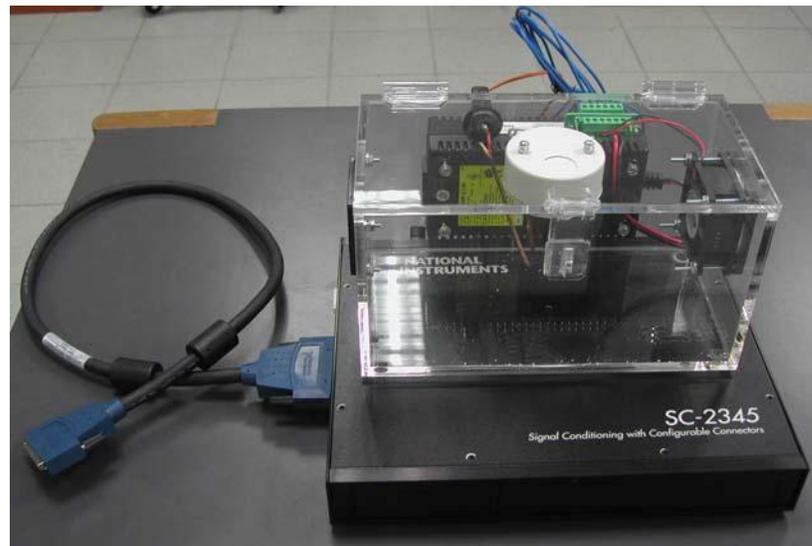
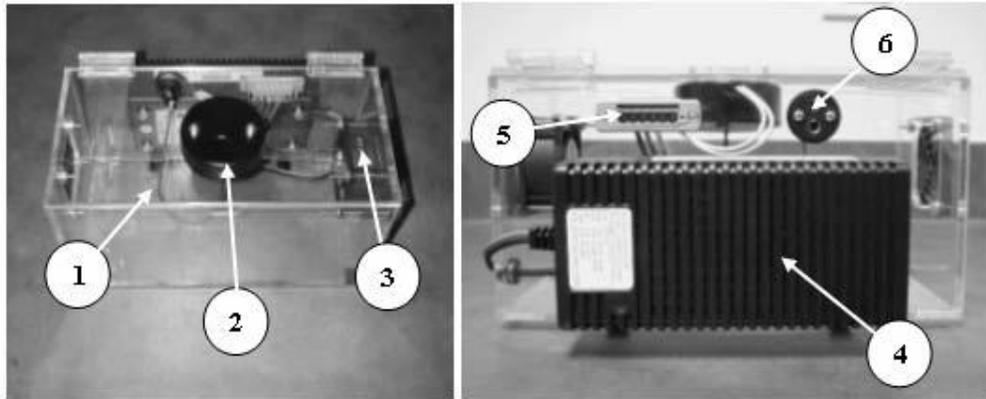


Figure 11: SETUP OF THERMAL CHAMBER SYSTEM



1. J-Type Thermocouple
2. 12V Light with 20W Halogen Bulb (draws 1.5A)
3. 12V Fan (draws 0.15A)
4. PS-3 Power Supply (13V 4A)
5. 6-position Terminal Receptacle
6. J-Type Thermocouple Receptacle

Figure 12: CONFIGURATION OF THE CHAMBER

III.1. RUNNING THE PROGRAM

Go to directory "C:\ee3302\feedforward".

Open the file "main-feedforward_thermal.vi".

III.2. CONTROL PANEL

A control panel has been designed to interface the user to the thermal chamber. The setup is similar to what you have handled in Part II: Feedforward Control System. The control panel and the underlying block diagram operations are shown in figure 13 and 14 respectively.

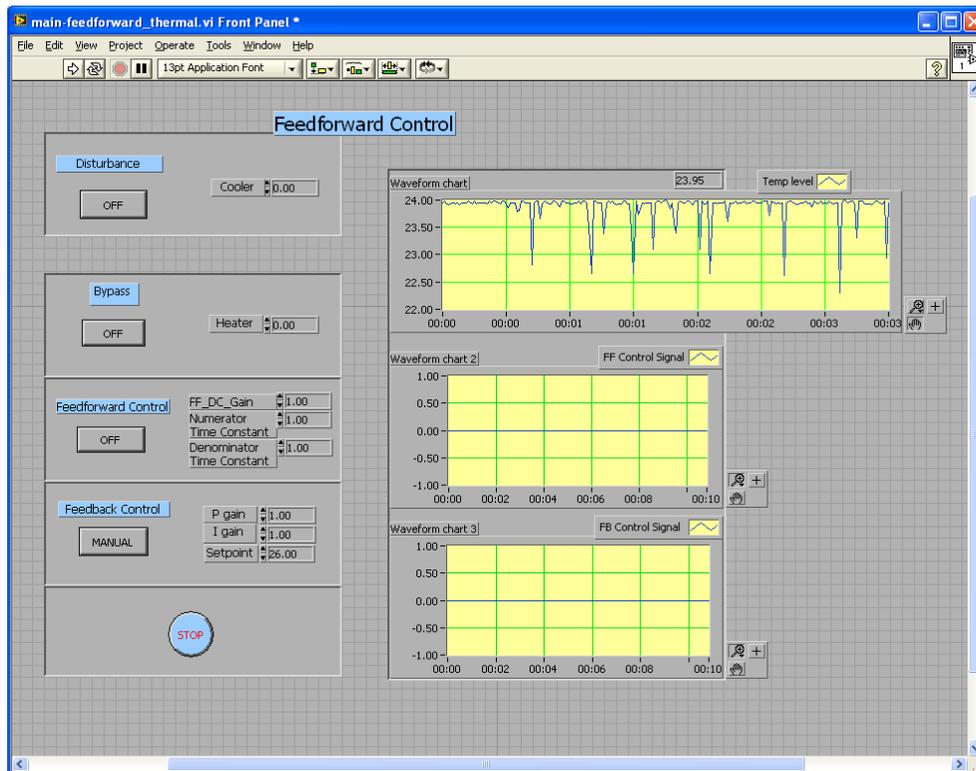


Figure 13: CONTROL PANEL OF THE THERMAL CHAMBER

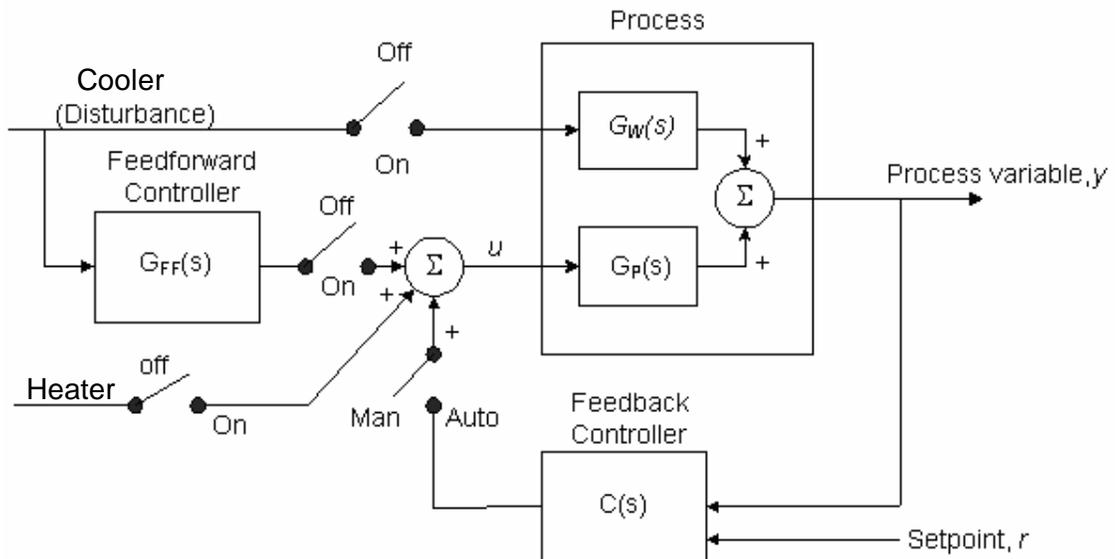


Figure 14: COMBINED FF/FB CONTROL CONFIGURATION OF THE THERMAL CHAMBER

III.3 System Modeling

Similar to what you have achieved in Part II.3 MODELLING FROM STEP TESTS, obtain the process and disturbance model for the thermal chamber.

$$G_w(s) = \underline{\hspace{10em}}$$

$$G_p(s) = \underline{\hspace{10em}}$$

Qn 3: Configure the control panel as follows: Disturbance to ON, FF Controller to OFF, Bypass to ON, FB Controller to MANUAL. Set the fan input at 0.5 and the light input at 0.2. Let the temperature in the chamber settle. Increase the light input to 0.5 and observe the response in the chamber temperature. After it settles, reduce the light input by the same amount (i.e. to 0.2) and observe the response. Is the response to the positive step symmetrical to the response to the negative step? If not, which response speed is faster? Please explain this phenomenon. Try to suggest how you can make the response more symmetrical.

III.4 PI Control

Configure the control panel as follows: Disturbance to OFF, FF Controller to OFF, Bypass to OFF, FB Controller to AUTO. The controller used is a PI controller. Adjust the PI control to achieve an overshoot of not more than 10% to a step change in the temperature set-point. (e. g. set-point changed from 28°C to 29°C, with an overshoot of under 0.1°C). Specify your final PI parameters.

Gain (P):

Reset (I):

Change Disturbance to ON. At steady state, increase the fan input from 0.0 to 0.8. Note the effect of this input in causing a deviation of the temperature from the set-point.

Maximum deviation of y due to disturbance:

III.5 PI Control with Feedforward Controller

With your experience gained from Part II, now design a feedforward controller, and shows that the control performance in terms of disturbance attenuation is indeed superior to feedback control alone. The control panel provided will be sufficient for you to carry out all the tests necessary to design the FF controller.

Maximum deviation of y (with FF control): _____

Qn 4: Unlike in software simulation, perfect disturbance rejection cannot be achieved in this case, explain.

Fine tune your FF controller to achieve better disturbance rejection. Record your final tuning values and the disturbance response after the fine tuning.

Maximum deviation of y after fine tuning: _____

The fine-tuned FF controller is:

DC Gain of FF Controller: _____

Zero of FF Controller: _____

Pole of FF Controller: _____

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."

Observe the combined FB-FF controller system output (y). Enter the proportion of contribution to the response you think is from

FF control action _____

FB control action _____

(Hint: you may infer the amount of control effort from each controller by observing their respective control signals).

e.g., for perfect disturbance rejection, the control actions are:

FF control action 100%

FB control action 0%

Qn 5: Explain the consequence of having a large portion of the disturbance rejection being enforced by the FB Controller (i.e. FB control action > 50%)

REPORT

For this experiment, you may attach the relevant parts of this lab manual, with the blanks duly filled, attached your discussion pertaining to the questions raised on a separate sheet. Conclude your report with a summary of the learning's you have derived from this experiment.

REFERENCE

D.E. Seborg, T.E. Edgar and D.A. Mellichamp, "Process Dynamics and Control", 2nd Ed., Wiley, 2004.