Date: _______________ Name: ___________________________________

LABORATORY EXERCISE 16
CHARACTERISTICS OF ADDITIVE FEEDFORWARD CONTROL

OBJECTIVE: To provide an opportunity to implement feedforward control; to practice feedforward tuning using (simulated) plant data, and to demonstrate the effect of feedforward control in disturbance elimination, both with and without feedback control.

PREREQUISITE: Completion of Laboratory Exercise 15, Characteristics of Cascade Control.

BACKGROUND: Most processes are affected by two or more influences, the manipulated variable (usually the output of a feedback controller) and one or more process disturbances or load changes. With pure feedforward control, the process disturbance is measured; this signal, perhaps after scaling and dynamic compensation) is used to drive the manipulated variable. In most practical applications, feedback and feedforward control are combined, with the feedback controller correcting for deficiencies in the feedforward control as well as for the effect of unmeasured disturbances.

There are two methods of combining feedback and feedforward control:

1) by *adding* the feedforward and feedback controller outputs
2) by *multiplying* the feedforward and feedback controller outputs.

Additive feedforward control is appropriate if the process is linear, both in its response to a disturbance (load change) and in its response to a change in controller output. It is also appropriate if there is no significant change from a nominal operating point. In many cases where a change in the feedrate is the most significant process disturbance, a better choice may be to use multiplicative feedforward control.

This laboratory exercise demonstrates additive feedforward control. Although the process is non-linear (the process gain, dead time and time constant all increase with decreasing process throughput), we will test the efficacy of additive feedforward control where the feed rate stays fairly close to its nominal value. We will also demonstrate the changing control loop characteristics at greater deviation of the disturbance from its nominal value. A subsequent laboratory exercise will then demonstrate multiplicative feedforward control.

While this program can represent any process which is subject to both a control input (manipulated variable) and a measurable form of load upset, it is helpful for the student to consider the variables displayed and the process phenomena in terms of a specific example. Therefore, it is recommended that the student consider this exercise as being representative of the process heater shown in Figure 1.

The process variable to be controlled is the outlet temperature; the load disturbances are changes in process flow through the heater. Feedback control (from the measured outlet temperature) and feedforward control (from a measure of the process flow) are combined to set the fuel flow set point. Thus fuel flow is the manipulated variable.

Changes in the process flow rate will have a dynamic influence on the heater outlet temperature, as will changes in the fuel flow rate. Thus the process can be abstracted into the block diagram shown in Figure 2. Transfer function A(s) represents the dynamic relation between process flow rate changes and outlet temperature. Transfer function B(s) represents the dynamic relation between fuel flow and outlet temperature.

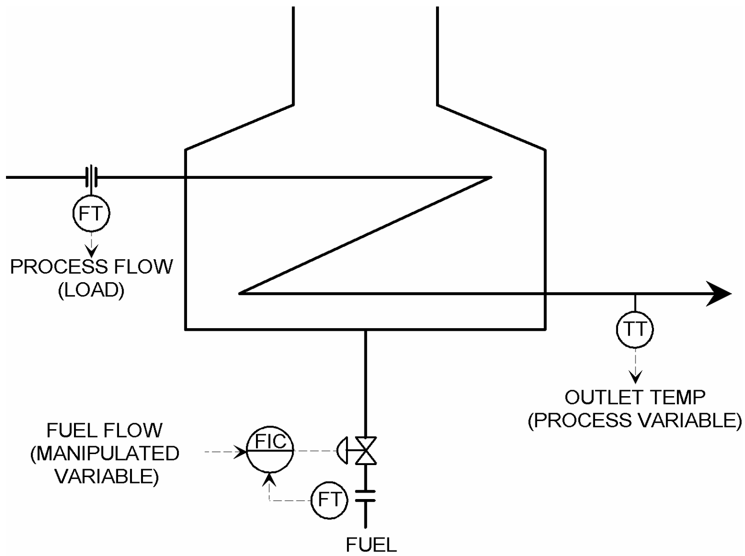

Figure 1
PROCESS HEATER

In the Feedforward control strategy, feedforward control is augmented by feedback trim. These signals are combined additively within the Primary controller; the output of the Primary controller then sets the set point of a Secondary controller. In essence, then, the Secondary controller set point is the manipulated variable by the combined feedback-feedforward control action. In addition to the usual Auto and Manual buttons, the Primary controller has a third button which toggles the feedforward control function ON or OFF; this provides for either enabling or disabling feedforward control. The Manual and Automatic switches of the Primary controller provide for either enabling or disabling feedback control. See Figure 3.

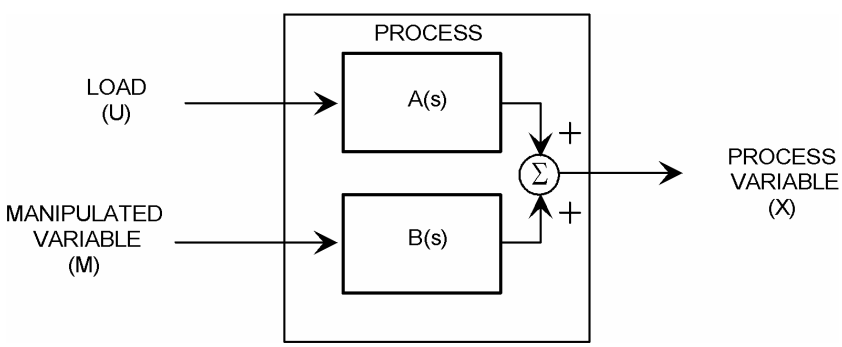

Figure 2
BLOCK DIAGRAM REPRESENTATION
OF PROCESS

Note that the dynamics which are preset into the process model have been chosen to illustrate feedforward control with dynamic compensation. It is not claimed that these dynamics are necessarily representative of an actual process heater. Through the Process selection from the Menu Bar and the subsequent “Change Parameters” option, the user may modify the process model dynamic terms to make the simulation representative of an actual process.

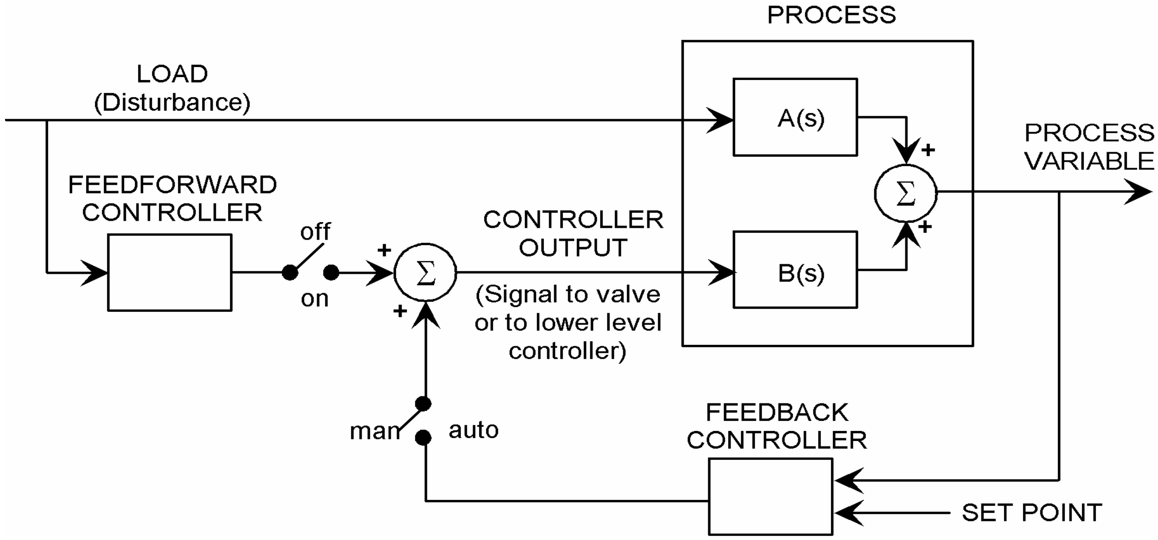

Figure 3
COMBINED FEEDFORWARD-FEEDBACK
CONTROL CONFIGURATION

1. RUNNING THE PROGRAM

Start **Windows**.

Run **PC-ControLAB**.

2. FEEDFORWARD CONTROL SET UP

After the title display, the initial operational display contains the Feedback control strategy. Change to the ADDITIVE FEEDFORWARD strategy:

> Select **Control | Select Strategy .** Click on "Ffwd_Add" from the subsequent drop-down menu.

Change to the HEATER process.

> Select **Process | Select** Model. Highlight "Heater" and click on **OPEN**.
>
> *The Feedforward control strategy provides a Primary and Secondary controller, similar to the Cascade and Ratio control strategies. The Secondary controller (labeled "Fuel Flow") is identical in function to that of the Cascade control strategy; it has Manual, Auto and Cascade switches. It must be in the Cascade mode before it will accept any form of signal, feedforward, feedback or combined, from the Primary controller.*
>
> *The Primary controller (labeled "Temperature") contains both the feedback (PID) function and the feedforward function. The MAN and AUTO buttons permit disabling or enabling feedback control; the FFWD button independently toggles feedforward control on or off. An LED on the Primary controller faceplate is dark green when feedforward control is off*

and bright green (or yellow) when feedforward control is on.

The Primary controller tuning function provides an access to feedforward controller tuning parameters. These consist of a feedforward gain, lead, lag and dead time settings.

Enter the following tuning parameters for the Secondary controller:

Gain:	0.5
Reset:	0.15 minutes/repeat

Put the Secondary controller in Auto and confirm acceptable operation by changing its set point to 40 KCFH (Thousand Standard Cubic Feet per Hour). If acceptable operation is observed, return its set point to the initial value.

To reduce the number of signals recorded, select **View | Variable Plot Selection**. Then select **NO** for Out-2, and Load-2. Select **YES** for Out-1.

In this exercise, the objective of the feedback-feedforward control system is to get the right set point to the secondary controller. We assume that the secondary controller has been properly tuned and is functioning correctly. Therefore we want to monitor its set point (primary controller output) and not worry about what its output is doing.

3. TESTING THE PROCESS

We will first make simulated plant tests to gain data which will enable us to determine initial feedforward controller tuning parameters.

Be sure that the Secondary controller is in Auto.

From the Primary controller faceplate, be sure that the feedforward controller is OFF (dark green LED) and that the feedback control is in Manual.

Select the Primary controller and press **StepIncr** to increase the process load (process flow rate) by 5% (20 GPM) of maximum value (400 GPM)

Observe the dynamic effect on the process variable (temperature). Record the following (Note: See Figures 1 and 2 in Laboratory Exercise 3for ways of estimating simple process model parameters from step test data). (Suggestion: Take advantage of the “Zoom” feature.)

Change in load (Δu): __20 GPM_ = ____5%__

Change in measurement (Δx): ____DegF_ = _____%__
(Be very careful about +/- sign!)

Process gain through the “A” path (K_{PA}): ____________________

Observed dead time (T_{dA}): ____________________

Observed first order lag time constant (τ_A): ____________________

Write this data in the form of a transfer function. Use the actual numerical values, rather than symbols for the process gain, dead time, etc:

A(s) = ______________________

With the Primary controller selected, press **StepDecr** twice to return the load to its initial value.

Now put the Secondary controller in Cascade. Select the Primary controller and increase its output (the Secondary controller set point) by 10% of full scale (What change in fuel flow rate does this represent?)

Observe the dynamic effect on the process variable (temperature). Record the following:

Change in manipulated variable (Δm):	______KCFH_ = ___10 %_
Change in measurement (Δx): (Be very careful about +/- sign!)	_______DegF_ = _____%_
Process gain through the "B" path (K_{pB}):	________________
Observed dead time (T_{dB}):	________________
Observed first order lag time constant (τ_B):	________________

Write this data in the form of a transfer function. Use the actual numerical values:

B(s) = ______________________

With the Primary controller selected, change its output back to the initial value (28%).

4. DETERMINATION OF FEEDFORWARD CONTROLLER TUNING VALUES

The required feedforward controller, in transfer function notation, is:

$$FF(s) = -\frac{A(s)}{B(s)}$$

Write this in its simplest form, using the actual numerical values from you process tests:

FF(s) = ____________________________

The feedforward control function in this program is pre-structured in the Primary controller; it consists of a steady state gain term, a lead lag term, and a dead time. Specifically, the feedforward controller can be represented by the following expression:

$$FF(s) = K_f \frac{T_{ld}s + 1}{T_{lg}s + 1} e^{-T_{dt}s}$$

where	K_f	=	Steady state (feedforward) gain
	T_{ld}	=	Lead time
	T_{lg}	=	Lag time
	T_{dt}	=	Dead time

You should be able to pick off numerical values for each of these parameters from the simplified transfer function FF(s) written above:

K_f = ____________

T_{ld} = ____________

T_{lg} = ____________

T_{dt} = ____________

Select the Primary controller; press **TUNE**, then select the **Feedwd** tab. Enter these feedforward controller tuning values. Press **Clear** to remove the dialog box.

5. TESTING THE FEEDFORWARD CONTROLLER

Now that the feedforward controller has been implemented, the next step is to test it and make any fine tuning adjustments which are necessary.

Put the Secondary controller in Cascade, to enable it to accept signals from the Primary. On the Primary controller press **Ffwd** to change the feedforward controller from OFF to ON. Observe that the LED changes from red to green.

In order to see the effect of feedforward control only, we will continue to leave the feedback portion of the Primary controller in Manual until we have completed the testing and fine tuning of the feedforward control.

What to Expect and not to Expect from the Feedforward Controller Tests:

*Suppose we make a load change using feedforward control alone; also suppose the process variable is **not** at the set point. We should **not** expect the feedforward controller to return the measurement to the set point. Rather we hope to see **no change** in the process variable. If there is any change, then we can fine tune either the feedforward controller gain or the dynamic compensation terms, as required. Once the feedforward controller has been fine tuned, then we can put the feedback controller on Automatic to bring the measurement to the set point.*

In a real-life application, the process variable would probably be near to the set point when we started making the tests for fine tuning the feedforward controller.

Press **StepDecr** once to make a load change (change the process flow rate). NOTE: Observe the record of the load variable. For this part of this exercise, do not change it to less than 280 GPM (70%) nor to more than 320 GPM (80%).

Was there any discernible change in the long term value of the process variable? _______

If so, then the feedforward controller needs fine tuning.

Consider the following:

If there is a decrease in the process flow rate, the fuel flow rate should decrease also (if you have the sign of the feedforward gain correct). If the long term value of the temperature decreased, then the indication is that the fuel was decreased to much, that is, the feedforward gain is too high. Reduce the gain slightly and try again. Consider another situation, such as increasing process flow and increasing fuel flow, but with the long term value of the temperature decreasing. This indicates that the feedforward gain is too low. Increase the gain and try again.

Once you get the temperature to remain fairly constant (say, within ± 5^0 for this exercise), then you can consider the dynamic effects, that is, what happens in the short term. Consider the following:

Suppose there is an increase in process flow, causing an increase in fuel flow rate. Suppose the temperature initially increases, then settles back to approximately the same value as the starting value. Obviously the feedforward gain is about right, but in the short term, there was an excess of fuel. Either the dead time is too short (the fuel flow rate was increased too soon) or the lead term is too large. Try changing these one at a time, then apply another load change.

Try to get the maximum deviation from the starting value no more than 5^0. Make step load changes only between 70% and 80%. Record your final tuning values, and the response of your final process load upset test:

K_f = ____________

T_{ld} = ____________

T_{lg} = ____________

T_{dt} = ____________

Maximum deviation of process variable from steady state point: ____________

In real applications, there is probably a law of diminishing returns where further testing to try to improve the feedforward controller is probably not worth the slight gain that may be made. At some point, it will be time to say, "We've tuned the feedforward controller enough."

To give the feedforward a more strenuous test, apply a random load variation. Press **AutoLoad** above the instrument faceplates.

Observe the response. You should see a load (process flow rate) varying continuously and automatically. The controller output (fuel flow set point) should vary in response to the load variations. If your feedforward controller is well tuned, the process variable (temperature) should be varying only a small amount, if at all.

Press **AutoLoad** again to remove random process load variations. Press **StepIncr** or **StepDecr** to return the load to somewhere between 70% and 80%.

6. ADDING FEEDBACK CONTROL

The “B” transfer function determined in part 2 is also in the feedback loop, hence the parameters of B(s) can be used for calculating feedback controller tuning values.

Use K_{pB}, T_{dB} and τ_B in the Ziegler-Nichols open-loop equations (see Table 1 in Laboratory Exercise 9) to calculate Gain and Reset for a PI controller.

Gain: ____________

Reset: ____________ minutes/repeat

Enter these values for the Primary controller, then put it in Automatic.

Does the process variable now come to the set point? _______

Change the set point from 275^0 to 300^0. Make any fine tuning adjustments necessary to the feedback controller. Final feedback controller tuning.

Gain: ____________

Reset: ____________ minutes/repeat

Turn **AutoLoad** back on. How much of the control action do you think is due to:

feedforward control action? _______________

feedback control action? _______________

If your feedforward controller is well tuned, once the measurement is brought to the set point, essentially all of the control action is the result of feedforward control; essentially none of the control action is the result of feedback control.

If your feedforward controller has some residual error in it (not completely well tuned) then you may
observe that there is more oscillation in the loop using both feedback and feedforward than there was using feedforward alone. In this case, the feedback controller may have to be “detuned” (i.e. lower the gain.)

Reason: If the feedforward controller is not perfectly tuned (which it probably will never be), then on a load change there will be some short term variation, even if there is no long term variation. If the feedback controller is tuned to tightly, it will try to correct for this short term variation, and will in turn introduce even more variation. Hence, in a feedback-feedforward system, do not attempt to tune the feedback controller too tightly.

7. A LOOK AT ADDITIVE FEEDFORWARD CONTROL WHEN THERE IS MORE DEVIATION FROM THE NORMAL OPERATING POINT.

The last section showed that, even with a non-linear process, if there is not a lot of deviation from the normal operating conditions (in this case, a set point of 275^0 and a process flow rate between 70% and 80%), then additive feedforward control did okay. But what if the process flow rate varies more than this?

Put the set point back at 275^0, and press **StepIncr** or **StepDecr** to bring the process flow rate to between 70 and 80%.

Change the set point to 280^0. Is the loop response okay? __________
(It should be.)

Change the set point back to 275^0 then press **StepIncr** to make the process flow rate between 90 and 100%. Then change the set point to 280^0. How does the loop respond, compared with its response with about 75% process flow.

____

(It should be slightly more sluggish.)

Put the set point back at 275^0, then press **StepDecr** in *slow* increments. Let the PV come to an equilibrium between steps. What do you observe the feedback control loop doing as the process flow rate is decreased?

____

You should have observed that the feedback loop became more oscillatory as the process flow rate decreased. Even to the point that if the process flow rate is decreased too much, the loop becomes unstable. This is because the process gain (primarily, but also the dead time and time constant) increase as the process flow rate decreases. The adverse effect is observed with feedback plus additive feedforward control, which dies not take into consideration the non-linearity of the process. The same effect would be noted if feedback control alone were used. The next exercise will demonstrate the advantages of multiplicative feedforward for this type of situation.