When you have completed this exercise, you will be familiar with the concept of cascade control and its application to a level/flow process.

The Discussion of this exercise covers the following points:

- Cascade control
- Tuning a cascade control system
  Secondary control modes.

The PID control systems we have studied thus far have used a single control loop. Although single-loop control may provide satisfactory results, other forms of advanced control are available and may prove to be more advantageous. Among these is cascade control.

Cascade control

The different measureable variables in a process are often interrelated to the extent that knowledge of an intermediate variable could be used beneficially to control a primary process variable. One example is a flow of water entering a tank in which the level is to be controlled. Controlling the incoming flow with a control valve certainly has a direct effect on the level of water in the tank. This is because the two variables, incoming flow and tank level, are interacting. Cascade control takes advantage of this inherent interaction between variables to improve the overall control on a process variable.

Cascade control utilizes two control loops: a master loop and a slave loop. The master loop contains the primary, or master controller and monitors the primary variable. The slave loop contains a secondary, or slave controller which monitors a second variable. The output of the master controller is connected to the set-point input of the slave controller, causing the two controllers to be cascaded.

Figure 2-42. Block diagram of a general cascade-control scheme.
The main purpose of cascade control is to minimize the disturbances that affect the secondary variable before they cause pronounced changes in the primary controlled variable. Another advantage is the improvement in the speed of response of the secondary variable.

The principle of cascade control is best illustrated by an example involving the control of the level of fluid in a tank through regulation of the output flow rate (the input flow rate is assumed to be constant). The typical single-loop control scheme is illustrated in Figure 2-43. In this case, the level of water in the tank is monitored directly by a single controller which activates the control valve to steer the measured level towards the set-point value. A sudden change in the output flow due to a change in the downstream load would result in a level change. The controller however cannot respond to this new situation until the new flow rate has had a measurable effect on the level in the tank.

Figure 2-43. Simple level control.

Figure 2-44 shows how the cascade scheme works around this shortcoming by using a second loop with a slave controller which monitors and controls the flow at the output of the system. The master controller still monitors the level in the tank but adjusts the set point of the slave controller instead of the control valve. The flow control loop regulates load changes before they have an important impact on the level.

Figure 2-44. Cascade control (Level/Flow).

Thus, a cascade control system does not have to wait for the primary controlled variable to change before initiating corrective action. A change in the secondary
controlled variable is sufficient to do so. Although a variation of the primary controlled variable can occur, this variation is typically not as important when it is under cascade control.

Cascade control is effective when the slave loop is more responsive than the master loop. A general rule of thumb states that the slave-loop time constant should be smaller than four to ten times the time constant of the master loop. If this is not the case, cascade control should be avoided because the system will tend to be unstable. Notice that it is also possible to cascade multiple loops in series as long as relevant process variables can be measured.

**Tuning a cascade control system**

The tuning of a cascade control system can be done as follows:

1. With the master controller in manual mode, the slave controller is tuned first. Normally, proportional (P) action only is utilized for the slave controller. However, integral (I) action is sometimes used when the process has a short time constant, as in the case of flow processes.

   Since the slave loop can be treated as if it were a single-control loop, the P and I (if any) constants of the slave controller can be determined using any of the previously presented methods of controller tuning.

2. Once the slave controller has been tuned, it is switched into automatic mode and the master controller is set for PI or PID control. The master loop can be considered a single-control loop because the slave loop can be treated as a final control element. Based on this assumption, the master controller can be tuned using any of the methods previously presented.

**Secondary control modes**

A few suggestions on the different control modes appropriate for the secondary loop (slave loop) in different specific situations:

- Control of flow is normally done in PI mode
- Valve positioners are usually controlled in proportional mode with a large gain ($K_C \approx 20$).
- Derivative action should be avoided if it acts on set-point changes as this causes overshoot. Some controllers are capable of applying the derivative action on the controlled variable only. Such a controller can be used profitably with derivative action in a secondary loop when the measured variable is not too tainted by noise.
The Procedure is divided into the following sections:

- Setup and connections
- Adjusting the differential-pressure transmitters
- Tuning the slave loop
- Tuning the master loop
- Controlling the level/flow cascade loop

Setup and connections

1. Connect the equipment according to the piping and instrumentation diagram (P&ID) shown in Figure 2-45 and use Figure 2-46 to position the equipment correctly on the frame of the training system.

<table>
<thead>
<tr>
<th>Name</th>
<th>Model</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential-pressure transmitter (high-pressure range)</td>
<td>46920</td>
<td>FIT 1</td>
</tr>
<tr>
<td>Differential-pressure transmitter (low-pressure range)</td>
<td>46921</td>
<td>LIT 1</td>
</tr>
<tr>
<td>Solenoid valve</td>
<td>46951</td>
<td>S</td>
</tr>
<tr>
<td>Controller (2 loops in cascade)</td>
<td>------</td>
<td>LIC</td>
</tr>
<tr>
<td>Venturi tube</td>
<td>46911</td>
<td>FE 1</td>
</tr>
<tr>
<td>Three-valve manifold</td>
<td>85813</td>
<td></td>
</tr>
</tbody>
</table>
The paperless recorder (UR) is not displayed in the P&ID above. See Figure 2-47 for the suggested electrical connections.
2. Connect the control valve to the pneumatic unit.

3. Connect the pneumatic unit to a dry-air source with an output pressure of at least 700 kPa (100 psi).

4. Wire the emergency push-button so that you can cut power in case of an emergency.

5. Do not power up the instrumentation workstation yet. Do not turn the electrical panel on before your instructor has validated your setup—that is not before step 11.
6. Connect the solenoid valve so that a voltage of 24 V dc actuates the solenoid when you turn the power on in step 11.

7. Connect the controller to the control valve and to the differential-pressure transmitters. You must also include the recorder in your connections. On channel 1 of the recorder, plot the level output signal from the first transmitter. On channel 2, plot the flow output signal from the second transmitter. Channel 3 is used to display the output of the cascade control scheme sent to the control valve. Be sure to use the analog inputs of your controller to connect the differential-pressure transmitters.

8. Figure 2-47 shows how to connect the different devices together.

![Figure 2-47. Connecting the instruments together for cascade control.](image)

The output of the master loop determines the set point of the slave loop in cascade control. This output is usually relayed internally to the slave loop when operating in cascade mode. However, some controllers do require a physical connection from the output of the master loop to the remote set-point port of the slave loop. The corresponding electrical connections shown above (in orange) might or not be required with your controller (consult the technical information related to your controller).

9. Before proceeding further, complete the following checklist to make sure you have set up the system properly. The points on this checklist are crucial elements for the proper completion of this exercise. This checklist is not exhaustive, so be sure to follow the instructions in the *Familiarization with the Training System* manual as well.
The solenoid valve under the column is wired so that the valve opens when the system is turned on.

All unused ports on the column are capped.

The hand valves are in the positions shown in the P&ID.

Valve HV3 is open to avoid pressurizing the column.

The pneumatic connections are correct.

The controller is properly connected to the differential-pressure transmitters and to the control valve.

10. Ask your instructor to check and approve your setup.

11. Power up the electrical unit, this starts all electrical devices as well as the pneumatic unit. Activate the control valve of the pneumatic unit to power the devices requiring compressed air.

12. In manual mode, set the output of the slave controller to 0%, then 100%. The control valve should be fully open in the first case and fully closed in the second case. If it is not, revise the electrical and pneumatic connections and make sure the calibration of the I/P converter is appropriate.

13. Test your system for leaks. Use the drive to make the pump run at low speed in order to produce a small flow rate. Gradually increase the flow rate up to 50% of the maximum flow rate that the pumping unit can deliver (i.e., set the drive speed to 30 Hz). Stop the pump and repair all leaks.

Adjusting the differential-pressure transmitters

14. Bleed the impulse line and configure the low-range differential-pressure transmitter for level measurement. Adjust the zero of the differential-pressure transmitter.

Set transmitter parameters so that a 4 mA signal is sent for a level of 0 m (0 in) and a 20 mA signal for a level of 0.75 m (30 in).

15. Connect the impulse lines of the high-range differential-pressure transmitter to the three-valve manifold. Bleed the impulse lines and configure the transmitter for flow measurement. Adjust the zero of the differential-pressure transmitter.

Set transmitter parameters so that a 4 mA signal is sent for a flow of 0 L/min (0 gal/min) and a 20 mA signal for a flow of 45 L/min (12 gal/min).
Tuning the slave loop

16. Tune the slave loop by using one of the methods presented in this unit (Trial and error method, Ultimate-cycle method, Open-loop Ziegler-Nichols method). Set the drive to 50 Hz.

Remember that the slave loop must be tuned independently of the master loop. You can do so directly with the appropriate loop on your controller or you can use a calibrator connected to the control valve if you want to characterize your process (disconnect the control valve from the controller while you characterize the process).

Record the control parameters obtained for the slave loop below. It is recommended that the PI mode be used for a flow slave loop.

\[ K_c = \]  
\[ T_i = \]

17. Set the slave loop according to the parameters you found in the previous step. Switch the slave control loop into Auto mode. This control loop should be kept in automatic mode for the remainder of this exercise.

Test the flow control loop and fine tune the parameters if required.

Tuning the master loop

The master loop could be tuned with any of the three methods presented in this manual but two are recommended in the next step. The first method relies on the fact that a very similar process was tuned in the previous exercise and constitutes a good starting point. The second method is the open-loop Ziegler-Nichols method. Choose the one you prefer.

The action of the master loop will be inverted with respect to the slave loop as an increase of the measured level causes a decrease of the output variable, i.e. a decrease of the flow set point (slave loop).

18. Trial and error method: Program the master controller for PI control with the parameters of Ex. 2-3 and test it in cascade mode. Fine-tune the parameters using the trial and error method if required.

Record the control parameters obtained for the master loop below.

\[ K_c = \]  
\[ T_i = \]
Open-loop Ziegler-Nichols method: Let the level process stabilize for a set point of the slave controller adjusted at 65%. Change the set point of the slave controller to 85% and wait for the level to stabilize again. (Be patient as this can take about twenty minutes). Transfer the data to a computer and determine the process parameters and the PID parameters:

\[ K_p = \quad t_d = \quad \tau = \] 

\[ \kappa = \frac{\tau}{t_d K_p} = \] 

Table 2-10. Ziegler-Nichols method – Master controller.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Proportional Gain $K_c$</th>
<th>Integral Time $T_i$</th>
<th>Derivative Time $T_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>$K_c = 0.9 \kappa =$</td>
<td>$T_i = 3.33 t_d =$</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>$K_c = 1.2 \kappa =$</td>
<td>$T_i = 2 t_d =$</td>
<td>$T_d = 0.5 t_d =$</td>
</tr>
</tbody>
</table>

Be careful with units. Your controller might use units different from those you used in Table 2-10.

Program the master controller with the parameters you just calculated and test it in cascade mode. Fine-tune the parameters if required.

Controlling the level/flow cascade loop

19. With your cascade controller properly set, create a 40% to 60% step change in the set point and observe the evolution of the system. Record and transfer the data to a computer. Plot a graph of your results.

20. Try different set-point values by increasing or decreasing the set point by step changes of 20%. Determine whether the controller tuning remains acceptable over a broad range of set points. Adjust the parameters if necessary.

21. Once the system is well tuned, set the controller to a set point of 50%.

Create a sudden change in the process load by closing valve HV4. Is the controller able to rapidly correct for the load change without oscillation of the controlled variable?
How much time is required for the process to return to the set point? How does this compare to conventional control with regard to the load change?

__________________________________________________________________________________________________________________________________________

22. Re-open valve HV4 and let the process stabilize again to the set point of 50%. Suddenly increase the drive speed to 60 Hz to create a disturbance in the flow input.

Is the system reacting in the same way as in the previous step? Can it handle the load change? How much time is required for the process to return to the set point?

__________________________________________________________________________________________________________________________________________

23. Stop the pump and empty the column.

24. Stop the system, turn off the power, and store the equipment.

CONCLUSION

This exercise let you explore the possibilities and peculiarities of cascade control in the classical case of a level/flow process. You observed the amelioration of the overall response of the control scheme to a disturbance at the expense of a slightly higher complexity. This exercise also concludes the unit on basic techniques of process control. The next unit will put together the concepts you have learned so far by focusing on the troubleshooting of control loops.

REVIEW QUESTIONS

1. What determines the set point of the slave controller in a cascade control scheme?

__________________________________________________________________________________________________________________________________________

2. What is the main purpose of cascade control?

__________________________________________________________________________________________________________________________________________
3. What is the minimum requirement for the input (controlled) variables of the master and slave controllers?

______________________________________________________________________________

4. In order for cascade control to be effective, should the slave process be more responsive or less responsive than the master process? Explain.

______________________________________________________________________________

______________________________________________________________________________

5. Briefly describe the procedure for tuning a cascade control system.

______________________________________________________________________________

______________________________________________________________________________