CHAPTER 7

DESIGN OF CASCADE CONTROLLER FOR
HYPERSONIC WIND TUNNEL

7.1 INTRODUCTION

The design of conventional controller discussed in Chapter 1 involves a single loop control that uses only one feedback signal. This signal is then compared to a set before being sent to the actuator (i.e. valve) that adjusts accordingly to meet the set point. Cascade control, in contrast, make use of multiple control loops that involve multiple signals (feedback) for one manipulated variable. Cascade control is one of the most commonly used control system structures in process plants.

It measures more system variables and fed back as process variables, creating sub control loops. Thus there is a master or main control loop and slave or auxiliary control loop. A simple cascade controller has two control loops for measuring two measurement signals that control one primary variable. Here the output of the primary controller determines the set point for the secondary controller, and the output of the secondary controller is used to adjust the control variable. In general, the change of the secondary controller is fast, while the primary controller changes slowly.

A cascade control structure involves two or more PID controllers in serial connection. For designing the cascade controller for hypersonic wind tunnel, the inner loop secondary controller is chosen as a simple P type
controller with high gain, while the outer loop primary controller is a conventional PI controller.

The P controller gives an output value that is proportional to the current error value. The response can be adjusted multiplying the error \( e(t) \) with a constant \( K_p \) called the proportional gain as given in equation 7.1

\[
u(t) = K_p e(t) \tag{7.1}\]

The block diagram showing the concept of cascade controller is given in Figure 7.1. The primary loop monitors the control variable while the secondary loop receives its set point from the primary loop and controls the reference variable accordingly.

Once cascade control is implemented, disturbances from rapid changes of the secondary controller will not affect the primary controller. Cascade controller makes the system to be more responsive to disturbances.

One of the main advantages of using cascade control is that disturbances affecting the inner loop can be compensated quickly in the slave loop than in the slower master loop. Cascade control is applicable when there
are more than one measurable variable in the process in addition to the main control variable and the inner control loop is significantly faster than the outer loop. If there is a disturbance affecting the inner loop of the system, this can be controlled well than with single-loop control.

### 7.2 SINGLE STAGE CASCADE CONTROLLER

The cascade controller is called as a single stage cascade controller if there is only one inner secondary control loop (slave), in addition to the master primary loop. The single stage cascade controller for hypersonic wind tunnel, has a simple P type controller with high gain as the inner loop secondary controller, while the outer loop primary controller is a conventional P-I controller.

![Figure 7.2 Block diagram of the system with single stage cascade controller.](image)

The block diagram of the HWT system with single stage cascade controller is shown in Figure 7.2. The primary loop contains the PI controller which receives the difference between given set point and process output ie, the error. So primary or master control loop measures the controlled variable.
and uses the set point applied by the operator. The secondary or slave loop is a P controller which receives its set point from the output of the primary loop. The other input is the pressure in the second chamber ie, the heater. The disturbance from the heater, which is reflected as pressure variations, is given to the secondary P controller loop, which is the slave controller, to take corrective action, before the disturbance affects the process. Thus, by using a single stage cascade controller, the disturbances from the internal states (heater pressure) are corrected by the slave controller and thus the final set point is reached in less time.

7.2.1 Design of Single Stage Cascade Controller

Cohen Coon tuning method is used to determine the controller parameters. To design the inner secondary P controller, apply a step input to the valve opening ‘m’. The process reaction curve is obtained as the output heater pressure. From the curve, the delay time $t_d=0.1$ sec, the time constant $\tau=12.9$ and process gain, $K=2.75$.

The proportional gain of the P controller is given by

$$K_p = \frac{\tau}{Kt_d} \left(0.9 + \frac{t_d}{12\tau}\right)$$

(7.2)

Substituting the values of process gain $K$, delay time $t_d$ and time constant $\tau$, obtained from the process reaction curve in equation (7.2), we get proportional gain, $K_p=42.24$.

The inner control loop in cascade with the settling chamber dynamics forms the process to the outer loop. For tuning the master controller, the dynamics of the above series combinations is to be determined. A step input to the inner control loop is given, and the process reaction curve at the output
of settling chamber is obtained. From the curve, the values of delay time 
\( t_d = 0.5 \text{ sec} \), time constant \( \tau = 12 \), and the process gain \( K = 2.4 \).

Substituting the values of process gain, delay time and time constant 
obtained from the process reaction curve in the equations for the proportional 
gain (equation 4.3) and integral time (equation 4.4), we get proportional gain 
as \( K_c = 9.71 \) and integral time as \( \tau_i = 1.54 \text{ sec} \).

The secondary master PI controller transfer function is formed using 
the calculated values of \( K_c \) and \( \tau_i \) as follows:

\[
\frac{U(s)}{e(s)} = 9.7 + \frac{6.29}{s}
\]  

\[ (7.3) \]

7.2.2 Implementation of Single Stage Cascade Controller

The step-by-step procedure of the simulation carried out for the 
Hypersonic Wind Tunnel system with Single Stage Cascade controller is 
given in this section.

1. Choose PI controller as the Primary or master controller, which 
receives the set point and P controller as the secondary or slave 
controller to control the effect of disturbances occurring in the second 
chamber ie, heater.

2. Determine the controller settings of the secondary P controller by 
giving a step input to the valve opening ‘m’, and the process reaction 
curve is obtained at the output of the heater ie, \( P_2 \).

3. Using the Cohen Coon method, determine the value of proportional 
gain, \( K_p \).
4. To find the primary PI controller parameters, obtain the process reaction curve by giving a step input to the inner control loop in cascade with the settling chamber.

5. From the curve, obtain the values of delay time $t_d$, and calculate time constant $\tau_i$ and the process gain $K_c$.

6. PI controller transfer function is formed using the calculated values of $K_c$ and $\tau_i$ and is included in the system as shown in the Figure 7.2.

7. The difference between the set point pressure and present output pressure in the settling chamber ie, error is given as input to the PI controller.

8. The difference between the output of the primary PI controller and the heater is given as input to the secondary P controller.

9. Simulations were done at different set points and the results obtained are tabulated for the various performance parameters.

7.3 TWO STAGE CASCADE CONTROLLER

For a two stage cascade controller, there are two secondary control loops (slaves) and a master primary controller. The two stage cascade controller for hypersonic wind tunnel has two simple P type controllers with high gain as the inner loop secondary controller. The outer primary loop will be a PI controller. Figure 7.3 shows the block diagram of the HWT system with two stage cascade controller.
Figure 7.3 Block diagram the system with two stage cascade controller.

As shown in Figure 7.3, there are two P controllers for the process. The innermost P controller receives the output from the first chamber ie, high pressure system and the output of the outer secondary controller. The main function of this innermost secondary loop is to take control actions based on the sudden changes in pressure of the high pressure system. The next secondary controller receives the output from the second chamber ie, heater and the output of the primary PI controller. This loop takes the corrective action if there are any disturbances in the heater pressure. Thus, by using a two stage cascade controller, the disturbances from the internal states (heater and high pressure system) are corrected before they affect the system and thus the system reaches the final set point faster than the system with PI controller alone.

7.3.1 Design of Two Stage Cascade Controller

Coohen Coon tuning method is used to determine the controller parameters. To design the inner most secondary P controller, apply a step input to the valve opening ‘m’. The process reaction curve is obtained as output pressure of high pressure system. From the curve, the delay time $t_d=0.1$ sec, the time constant $\tau=12.8$ and process gain, $K=2.8$. Substituting the
values of process gain $K$, delay time $t_d$ and time constant $\tau$, obtained from the process reaction curve in equation for the proportional gain (equation 7.2), we get proportional gain, $K_{p1}=41.16$.

The next inner secondary controller parameters are obtained by giving a step input to the innermost P controller designed above with heater cascaded to it. The process reaction curve is obtained as the output of the heater pressure. From the curve, the delay time $t_d=0.1$ sec, the time constant $\tau=12.4$ and process gain, $K=2.4$.

Substituting the values of process gain $K$, delay time $t_d$ and time constant $\tau$, obtained from the process reaction curve in the equation for proportional gain (equation 7.2), we get proportional gain, $K_{p2}=46.5$.

The two inner control loops in cascade with the settling chamber dynamics forms the process to the outer loop. To determine the dynamics of the master controller, a step input is given to the inner control loop with inner most loop and the process reaction curve is obtained as the output of the settling chamber pressure $P_3$. From the curve obtained, the values of delay time $t_d=0.5$ sec, time constant $\tau=12.5$, and the process gain $K=2.3$ are calculated and obtained.

Substituting the values of process gain, delay time and time constant obtained from the process reaction curve in the equations for the proportional gain (equation 4.3) and integral time (equation 4.4), we get proportional gain as $K_c=9.8$ and integral time as $\tau_i=1.54$ sec and the master PI controller as

$$\frac{U(s)}{e(s)} = 9.8 + \frac{6.4}{s}$$

(7.4)
7.3.2 Implementation of Two Stage Cascade Controller

The step-by-step procedure of the simulation carried out for the HWT system with two stage cascade controller is given in this section.

1. Select PI controller as the Primary or Master controller, which receives the set point and two P controllers as the Secondary or Slave controllers to control the effect of disturbances occurring in the first and second chamber ie, high pressure system and heater.

2. Determine the controller settings of the innermost secondary P controller, by giving a step opening to the valve ‘m’, and the process reaction curve is obtained at the output of the high pressure system ie, P_1.

3. Using the Cohen Coon method, determine the value of proportional gain, K_{p1} for the innermost P controller.

4. Determine the controller settings of the next secondary P controller, by giving a step input to the innermost control loop in series with the heater chamber dynamics, and the process reaction curve is obtained at the output of the heater ie, P_2.

5. Using the Cohen Coon method, determine the value of proportional gain, K_{p2} for the second slave P controller.

6. After including the two secondary P controllers in the HWT system, the primary PI controller parameters calculated using the Cohen Coon method. A step input is given to the secondary control loop with tertiary loop within it and the settling chamber dynamics in series to it.
7. Process reaction curve is plotted with settling chamber pressure Vs time. From the curve, obtain the values of delay time $t_d$ and calculate time constant $\tau_i$ and the process gain $K_c$.

8. PI controller transfer function is formed using the calculated values of $K_c$ and $\tau_i$ and is included in the system as shown in the Figure 7.3.

9. The difference between the set point pressure and present output pressure in the settling chamber ie, error is given as input to the PI controller.

10. The difference between the output of the primary PI controller and the heater pressure is given as input to the next secondary P controller.

11. The difference between the output of the secondary controller and pressure inside the high pressure system is given as input to the innermost P controller.

12. Simulations were done at different set points and the results obtained are tabulated for the various performance parameters.

### 7.4 RESULTS AND DISCUSSION

Servo and regulator operations of the single stage cascade controller and two stage cascade controller are performed for various set points from 60 bar to 150 bar. In servo operation, ability of the controller to track changes in set point is evaluated. In regulator operation, an external disturbance in the form of a pulse signal of amplitude 1 bar, and time period 5 sec is applied when the system output is at its set point.

#### 7.4.1 Response of Single Stage Cascade controller

Figure 7.4 and Figure 7.5 shows the servo operation of the controller for the set points of 70 bar and 100 bar.
Figure 7.4 Servo operation of single stage cascade controller at set point of 70 bar

Figure 7.5 Servo operation of single stage cascade controller at set point of 100 bar

Table 7.1 shows the performance analysis of the controller for different set points.
Table 7.1 Performance parameters for servo operation of single stage cascade controller at different set points.

<table>
<thead>
<tr>
<th>Set Point (bar)</th>
<th>Settling time (sec)</th>
<th>Delay time (sec)</th>
<th>Rise time (sec)</th>
<th>% Overshoot</th>
<th>Max. Possible Test Duration (sec)</th>
<th>IAE</th>
<th>ISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>10.02</td>
<td>1.93</td>
<td>3.26</td>
<td>11.15</td>
<td>420</td>
<td>1.39E+08</td>
<td>6.34E+14</td>
</tr>
<tr>
<td>70</td>
<td>9.271</td>
<td>2.109</td>
<td>3.639</td>
<td>6.27</td>
<td>341</td>
<td>1.42E+08</td>
<td>7.94E+14</td>
</tr>
<tr>
<td>80</td>
<td>8.261</td>
<td>2.293</td>
<td>3.975</td>
<td>3.02</td>
<td>275</td>
<td>1.61E+08</td>
<td>1.03E+15</td>
</tr>
<tr>
<td>90</td>
<td>8.288</td>
<td>2.428</td>
<td>4.719</td>
<td>0</td>
<td>224</td>
<td>1.76E+08</td>
<td>1.29E+15</td>
</tr>
<tr>
<td>100</td>
<td>8.21</td>
<td>2.56</td>
<td>11.46</td>
<td>0</td>
<td>176</td>
<td>1.97E+08</td>
<td>1.60E+15</td>
</tr>
<tr>
<td>110</td>
<td>8.02</td>
<td>2.73</td>
<td>15.5</td>
<td>0</td>
<td>147</td>
<td>2.17E+08</td>
<td>8.90E+15</td>
</tr>
<tr>
<td>120</td>
<td>8.1</td>
<td>2.92</td>
<td>12.1</td>
<td>0</td>
<td>115</td>
<td>2.45E+08</td>
<td>2.36E+15</td>
</tr>
<tr>
<td>130</td>
<td>7.98</td>
<td>3.05</td>
<td>11.76</td>
<td>0</td>
<td>87</td>
<td>2.16E+08</td>
<td>1.28E+15</td>
</tr>
<tr>
<td>140</td>
<td>8.18</td>
<td>3.2</td>
<td>10</td>
<td>0</td>
<td>60</td>
<td>2.97E+08</td>
<td>3.29E+15</td>
</tr>
<tr>
<td>150</td>
<td>10.91</td>
<td>3.33</td>
<td>11.5</td>
<td>0</td>
<td>35</td>
<td>3.54E+08</td>
<td>3.88E+15</td>
</tr>
</tbody>
</table>

It can be noticed from the Table 7.1 that for medium to high values of set point, there is no overshoot for the system response. Slight overshoot are present in the lower values of set points. The settling time is minimum for medium values of set point. The test duration decreases with the increase in set point.

Figure 7.6 and Figure 7.7 show the regulator operation of the controller. It is seen from the graph that the set point is not attained by the system, when the system is disturbed. The same is the condition for all the set points which can be seen from the Table 7.2.
Figure 7.6 Regulator operation of single stage cascade controller at set point of 70 bar

Figure 7.7 Regulator operation of single stage cascade controller at set point of 100 bar
Table 7.2 Performance parameters for regulator operation of single stage cascade controller at different set points.

<table>
<thead>
<tr>
<th>Set Point (bar)</th>
<th>Settling time (sec)</th>
<th>IAE</th>
<th>ISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>Not Settling</td>
<td>1.35E+08</td>
<td>9.58E+14</td>
</tr>
<tr>
<td>70</td>
<td>Not Settling</td>
<td>1.32E+08</td>
<td>8.55E+14</td>
</tr>
<tr>
<td>100</td>
<td>Not Settling</td>
<td>1.68E+08</td>
<td>9.31E+14</td>
</tr>
<tr>
<td>120</td>
<td>Not Settling</td>
<td>1.94E+08</td>
<td>8.87E+14</td>
</tr>
<tr>
<td>150</td>
<td>Not Settling</td>
<td>1.77E+08</td>
<td>5.72E+14</td>
</tr>
</tbody>
</table>

7.4.2 Response of Two Stage Cascade Controller

The servo operation of the system with two stage cascade controller for the set points of 70 bar and 100 bar are shown in Figure 7.8 and Figure 7.9.

Figure 7.8 Servo operation of two stage cascade controller at set point of 70 bar
Figure 7.9 Servo operation of two stage cascade controller at set point of 100 bar

Table 7.3 Performance parameters for servo operation of two stage cascade controller at different set points.

<table>
<thead>
<tr>
<th>Set Point (bar)</th>
<th>Settling time (sec)</th>
<th>Delay time (sec)</th>
<th>Rise time (sec)</th>
<th>% Over Shoot</th>
<th>Max. Possible Test Duration (sec)</th>
<th>IAE</th>
<th>ISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>7.876</td>
<td>1.925</td>
<td>4.046</td>
<td>0</td>
<td>428</td>
<td>1.31E+08</td>
<td>6.01E+14</td>
</tr>
<tr>
<td>70</td>
<td>8.301</td>
<td>2.11</td>
<td>11.52</td>
<td>0</td>
<td>345</td>
<td>1.75E+08</td>
<td>8.58E+14</td>
</tr>
<tr>
<td>80</td>
<td>7.029</td>
<td>2.122</td>
<td>9.42</td>
<td>0</td>
<td>282</td>
<td>1.63E+08</td>
<td>1.02E+15</td>
</tr>
<tr>
<td>90</td>
<td>6.91</td>
<td>2.449</td>
<td>10.44</td>
<td>0</td>
<td>234</td>
<td>1.71E+08</td>
<td>1.26E+15</td>
</tr>
<tr>
<td>100</td>
<td>7.33</td>
<td>2.59</td>
<td>12.71</td>
<td>0</td>
<td>193</td>
<td>2.22E+08</td>
<td>1.65E+15</td>
</tr>
<tr>
<td>110</td>
<td>7.8</td>
<td>2.74</td>
<td>13.0</td>
<td>0</td>
<td>164</td>
<td>2.22E+08</td>
<td>1.95E+15</td>
</tr>
<tr>
<td>120</td>
<td>7.62</td>
<td>2.92</td>
<td>12.43</td>
<td>0</td>
<td>136</td>
<td>2.49E+08</td>
<td>2.35E+15</td>
</tr>
<tr>
<td>130</td>
<td>7.96</td>
<td>3.05</td>
<td>13.12</td>
<td>0</td>
<td>113</td>
<td>2.68E+08</td>
<td>2.77E+15</td>
</tr>
<tr>
<td>140</td>
<td>8.2</td>
<td>2.19</td>
<td>13.46</td>
<td>0</td>
<td>95</td>
<td>2.97E+08</td>
<td>3.27E+15</td>
</tr>
<tr>
<td>150</td>
<td>8.58</td>
<td>3.35</td>
<td>10</td>
<td>0</td>
<td>77</td>
<td>3.17E+08</td>
<td>3.80E+15</td>
</tr>
</tbody>
</table>
From the Table 7.3, which gives the performance parameters of two stage cascade controller for different set points, it is seen that the controller does not have overshoot in any of the set points. The settling time for the medium values of set points are slightly less compared to the other values. The output remains constant at the set point for more time when low values of set points are given.

Figure 7.10 and Figure 7.11 shows the operation of the two stage cascade controller, by giving a disturbance when the system is at the set points of 70 bar and 100 bar.

Figure 7.10 Regulator operation of two stage cascade controller at set point of 70 bar
Figure 7.11 Regulator operation of two stage cascade controller at set point of 100 bar

Similar graphs for different set points are obtained and the corresponding values are noted and tabulated in Table 7.4.

Table 7.4 Performance parameters for regulator operation of two stage cascade controller at different set points.

<table>
<thead>
<tr>
<th>Set Point (bar)</th>
<th>Settling time (sec)</th>
<th>IAE</th>
<th>ISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>28.8</td>
<td>1.02E+07</td>
<td>7.23E+12</td>
</tr>
<tr>
<td>70</td>
<td>29.4</td>
<td>9.56E+06</td>
<td>6.28E+12</td>
</tr>
<tr>
<td>100</td>
<td>28.4</td>
<td>7.68E+06</td>
<td>4.59E+12</td>
</tr>
<tr>
<td>120</td>
<td>30</td>
<td>1.67E+07</td>
<td>8.76E+12</td>
</tr>
<tr>
<td>150</td>
<td>26.7</td>
<td>2.75E+06</td>
<td>7.06E+11</td>
</tr>
</tbody>
</table>

Unlike the single stage cascade controller, the two stage cascade controller is working well for the regulator operation. In every set point, the
two stage cascade controller is able to settle the pressure at the desired set point, following a disturbance.

7.5 SUMMARY

The pressure in the settling chamber of a hypersonic wind tunnel is controlled by using a single stage cascade controller and two stage cascade controller. Different performance parameters for the servo operation and regulator operation are obtained and tabulated for analysis. The advantageous thing that is seen in the servo operation of the cascade controller is the absence of overshoot. All other controllers designed so far, has some overshoot. At the same time, other performance indices are also not deteriorated. Regarding the regulator operation, the single stage cascade controller is not suitable, since it cannot tolerate the sudden disturbances.