Some Conventional Process Control Schemes

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Aims and Objectives

To revise / revisit basic control schemes covered in the second year control course (**Process Control I**). Schemes to be discussed are:

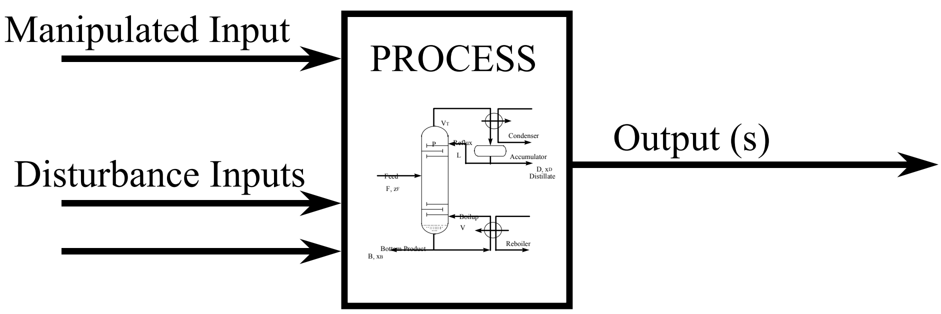
- Feedback control
- Feedforward Control
- Cascade Control
- Ratio Control

For each scheme a typical process example is used to highlight the application of the methodology.

On completion of this section of the course you should have an awareness of a common process control schemes and a basic knowledge of their advantages and disadvantages.

Background

Normally a chemical process has numerous inputs and many outputs. Consider the diagram below:



The inputs can generally be classified as:

- **Disturbances**. Disturbances are variables that fluctuate and cause the process output to move from the desired operating value (setpoint). A disturbance could be a change in flow, temperature of the surroundings, pressure etc. Disturbance variables (dv's) can normally be further classified in terms of measured or unmeasured signals.
- **The manipulated variable (mv)**. This is the variable chosen to affect control over an output variable. As the output is being controlled it is normally referred to as the controlled variable (cv). On a typical chemical process there are generally many cv's and and mv's. How the mv's are 'paired with' the cv's will be discussed in later notes.

The objective of a control system is to keep the cv's at their desired values (or setpoints). This is achieved by manipulating the mv's using a control algorithm.

Feedback Control

A basic feedback control system is shown in Figure (1). The objective is to control the temperature of the outlet stream of the shell and tube heat exchanger. The temperature is therefore the cv. The mv is coolant flow. Typical dv's would include inlet temperature, inlet flow, ambient temperature, etc.

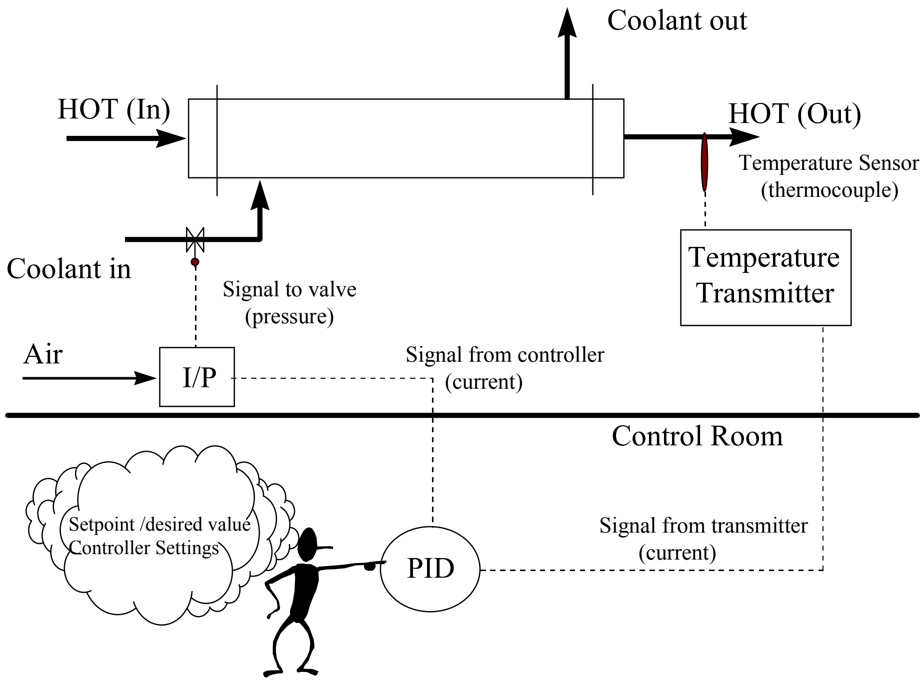
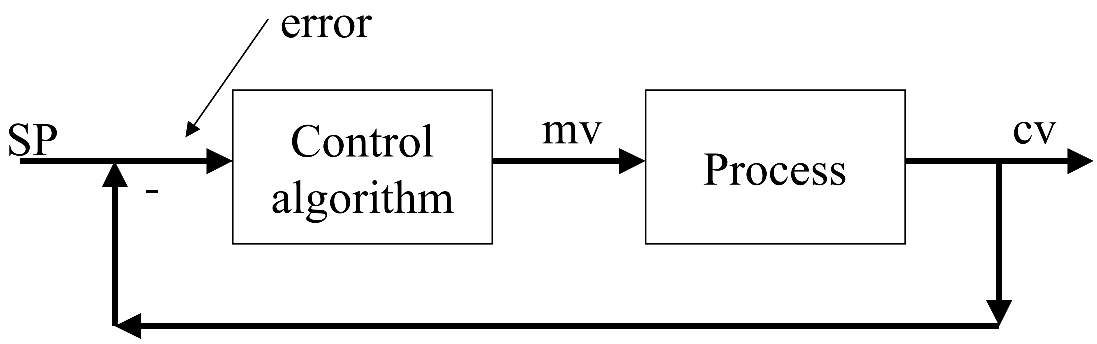


Figure (1). Feedback control scheme.

If the cv is not at setpoint then the objective of the controller is to adjust the mv to ensure that the desired level of operation is obtained.

It is easier (believe it or not) to visualise the control system in terms of a block diagram. A possible block diagram for the feedback control system is ,



This diagram neglects many elements (such as the measurement dynamics, control valve dynamics etc.) that are part of a standard feedback loop. This can generally be justified as the time constants associated with the measurement, the control valve etc. are normally negligible when compared to the time constant of the process. Note that the feedback controller is 'driven' by the error between the actual process output and the setpoint. Generally, the feedback controller is of the Proportional-Integral-Derivative (PID) type (this algorithm will be discussed in more detail later in the course).

Revision Exercises

1. What is the mathematical structure of a 1^{st} order plus dead-time process transfer function? Describe a procedure that could be used to determine the coefficients of this model.
2. What is the mathematical structure of a PID control law (in the Laplace domain)?
3. What is meant by the term closed loop equation?
4. If the controller transfer function were represented by the symbol $G_c(s)$ and the process transfer function $G_p(s)$ what is the closed loop equation that describes the response of the cv when the system undergoes a change in SP ?

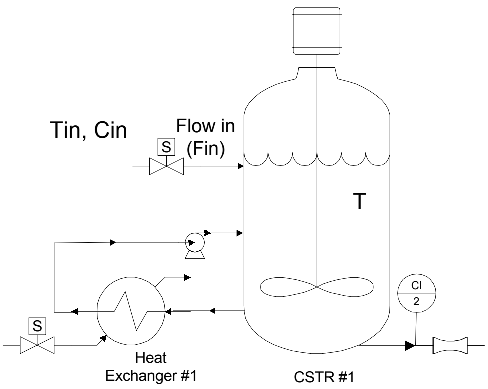
Feedforward Control

A feedforward control law is used to compensate for the effect that measured dv's may have on the cv. The basic idea is to measure a disturbance directly and take control action to eliminate its impact on the process output. How well the scheme will work depends on the accuracy of the process and disturbance models used to describe the system dynamics. Feedforward control actually offers the potential for perfect control. However, because of

Plant Model Mismatch (PMM) and unmeasured / unknown disturbances this is rarely achieved in practice. Consequently, feedforward control is normally used in conjunction with feedback control. The feedback controller is used to compensate for any model errors, unmeasured disturbances etc. and ensure offset free control.

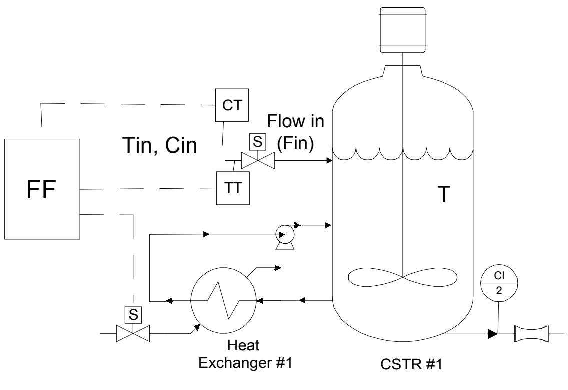
Feedforward Control of a Continuous Stirred Tank Reactor

The reactor system under consideration is shown below. The reactor is fed by a stream rich in reactant A, of concentration $C_{A(in)}$ and flowrate $F_{(in)}$. Within the system the following exothermic reaction take place, A→ B → C. Reactant A is converted to product B, but at high temperatures B undergoes further reaction and is transformed to undesired by-product C. The reactor is cooled by means of a heat exchanger.



The objective is to maintain the temperature of the reaction mass at the desired value when subjected to changes in inlet concentration (Cin) and temperature (Tin).

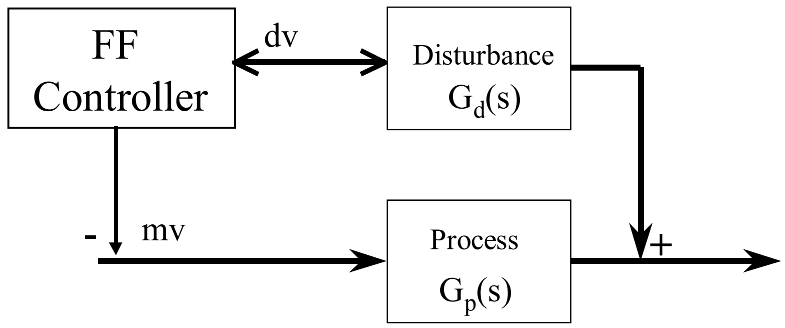
Thus, the cv is reactor liquid temperature, the mv is the coolant flowrate to the heat exchanger and the dv's are inlet concentration and inlet stream temperature. The feedforward control loop may be configured as follows,



Here, 'FF' represents the feedforward control algorithm, 'CT' and 'TT' are symbols used to describe the composition and the temperature transmitters.

So, the disturbances are measured and passed to a 'FF' device that calculates the necessary coolant flowrate to compensate for any cv moves when the measured dv deviates from it's nominal value.

Feedforward control: a block diagram description



$G_p(s)$ is a symbol used to represent the process dynamics. This is the relationship between the coolant flow (the mv) and the temperature (the cv). This could be a 1st order plus dead-time transfer function.
$G_d(s)$ is a symbol used to describe the mathematical relationship between inlet concentration and reactor temperature.
The feedforward controller calculates the appropriate mv to ensure the cv remains at SP.

Mathematical Details of the algorithm

Suppose that both the disturbance and the process dynamics are described by 1st order transfer functions,

$$G_p(s) = \frac{K_p}{\tau_p s + 1} \text{ and } G_d(s) = \frac{K_d}{\tau_d s + 1}$$

The feedforward control law is given by,

$$G_F(s) = G_d(s)/G_p(s) = mv/dv$$

Therefore the transfer function describing the feedforward control law is,

$$G_f(s) = \frac{K_d(\tau_p s + 1)}{K_p(\tau_d s + 1)}$$

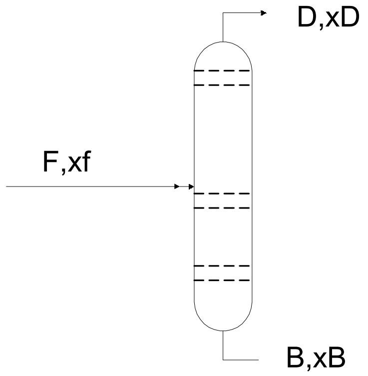
The numerator dynamics is often referred to as the ‘lead’ element while the denominator dynamics is termed the ‘lag’. Often, dynamic elements are ignored (e.g. to simplify implementation) leaving a gain only element,

$$G_f(s) = K_d/K_p$$

This is a very simple algorithm to implement.

Feedforward control using steady-state models from chemical engineering fundamentals

While notes in control enginnering texts tend to concentrate on transfer function process descriptions, fundamental chemical engineering concepts should not be forgotton entirely. Consider the following binary distillation column,



where F, D and B are the feed, distillate and bottoms flows (kmols/min) and xB and XD are the compositions of the more volatile component (mvc) in the bottoms and distillate stream respectively (mol %) . The objective is to design a feedforward control law to maintain x_D at the desired value when the column is subjected to changes in feedflow (F) and feed composition (x_f). The chosen manipulated variable is the distillate flowrate (D). To complicate matters, measurements of x_D and x_B are not available.

To design the feedforward control law we need the mathematical relationships between x_D and D, F and x_f. As discussed in earlier lectures, this information could be obtained from plant experimentation. However, being chemical engineers we know that the relationship between these variables is also available through the fundamental mass balance relationships,

$$F = D + B$$

$$Fx_f = Dx_D + Bx_B$$

Eliminating B from the component balance yields the desired relationship between x_D and D, F and x_f. This is given by,

$$D = F(x_f - x_B) / (x_D - x_B)$$

x_D and x_B are not measured, but may be replaced by their desired values (x_B^{SP} and X_D^{SP}) to give,

$$D = F(x_f - x_B^{SP}) / (x_D^{SP} - x_B^{SP})$$

This is a feedforward control law, it calculates the mv based upon dv and SP information. It is a steady-state (gain only) algorithm.

Revision exercise

1. Provide a mathematical analysis that justifies why a feedforward control law is given by $G_F(s) = G_d(s)/G_p(s)$

Cascade Control

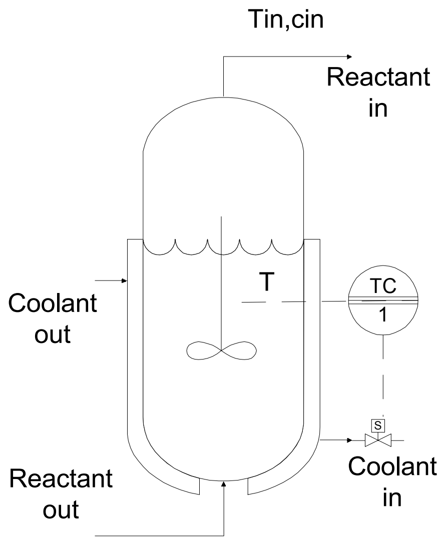
Cascade control is widely used within the process industries. Conventional cascade schemes have two distinct features:

- There are two nested feedback control loops. There is a secondary control loop located inside a primary control loop.
- The primary loop controller is used to calculate the setpoint for the inner (secondary) control loop.

Cascade control is used to improve the response of a single feedback strategy. The idea is similar to that of feedforward control: to take corrective action in response to dv's (which are not necessarily measured) before the cv deviates from setpoint. The secondary control loop is located so that it recognises the upset condition sooner than the primary loop.

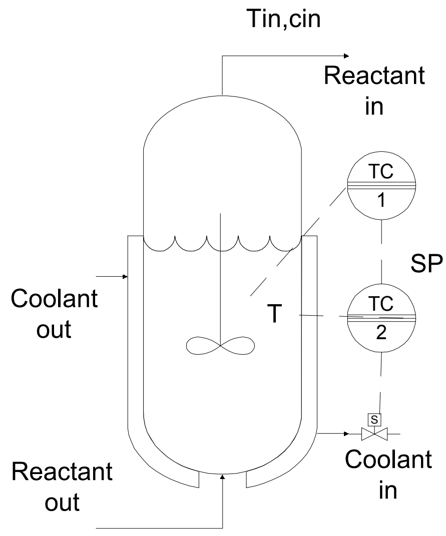
Cascade control of a CSTR

Figure (2) shows a conventional feedback control scheme on a CSTR. Here temperature is being controlled using coolant flowrate to a cooling jacket.



TC = temperature controller

Figure (2) A conventional feedback control scheme on a CSTR.



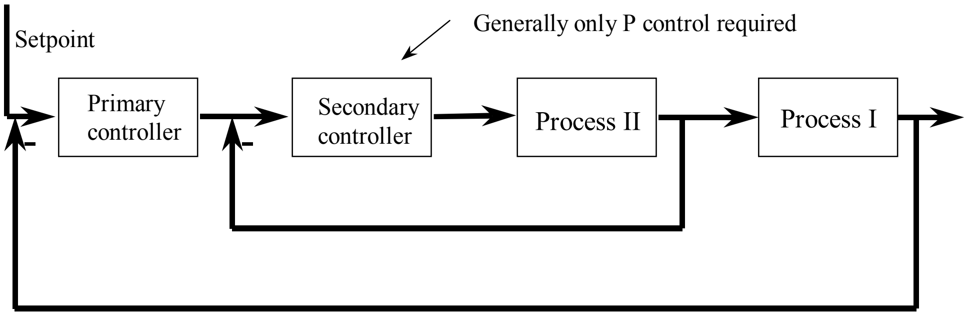
TC = temperature controller

Figure (3) A cascaded feedback control scheme on a CSTR.

Figure(3) shows a cascade control scheme on the same CSTR. The idea of the cascade strategy is to improve the control of temperature specifically with regard to changes in coolant temperature. Thus the inner loop controller takes control action to mitigate the effect of coolant temperature disturbances on the temperature of the reaction mixture.

Cascade control: a block diagram description

The normal block diagram representation of a cascade control loop is shown below,



Block diagram analysis may be used to develop the closed loop characteristic equation for this system in exactly the same fashion as that of a standard feedback loop.

Revision exercise

1. Suppose that the secondary loop process dynamics are represented by the symbol $G_{ps}(s)$ and the seconary loop controller by $G_{cs}(s)$. While the primary loop dynamics for the process and the controller are given by $G_{pp}(s)$ and $G_{cp}(s)$. Derive the closed loop transfer function describing the response of the primary controlled output to a change in the primary setpoint.

Ratio Control

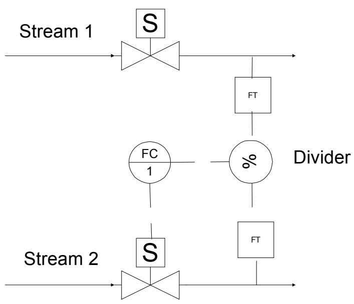
The objective of a ratio contol scheme is to keep the ratio of two variables at a specified value. Thus, the ratio (R) of two variables (A and B),

$$R = A / B$$

Is controlled rather than controlling the individual variables. Typical ratio control schemes include:

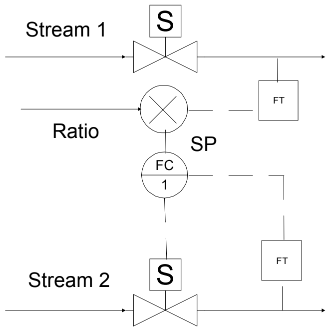
- Maintaining the reflux ratio for a distillation column.
- Maintaining the stoichiometric ratio of reactants to a reactor.
- Maintaining air/fuel ratio to a furnace.

Implementation: method I



The flowrate of the two streams is measured and their ratio calculated using a 'divider' (just a piece of extra electronics). The output of the divider is sent to the ratio controller (which is actually a standard PI controller). The controller compares the actual ratio with that of the desired ratio and computes any necessary change in the manipulated variable

Implementation: method II



Here one stream is under standard feedback control. The flow of the second stream is measured and sent to a 'multiplier' (again just a piece of extra electronics) which multiplies the signal by the desired ratio yielding the setpoint for the feedback control law.

Final Remarks

Conventional control schemes can be used 90%+ of the time within the process industries. The only drawback to success lies in the understanding correct implementation of a particular scheme. The aim of these notes was to provide a basic review of various control schemes (the methods were covered in much greater detail in process control I). On its own, this knowledge is not particularly useful: anyone can regurgitate text-book information. It is through process knowledge and understanding that appropriate control schemes are chosen and, it is the choice of the most appropriare scheme that is cruitial to sucessful implementation.

Revision Exercise

1. Provide a diagram showing feedback, feedforward and cascade control loops on a distillation column. Discuss the objectives of each loop.