Feedforward Control

So far, most of the focus of this course has been on feedback control. In certain situations, the performance of control systems can be enhanced greatly by the application of feedforward control. What you need to look for are two key characteristics:

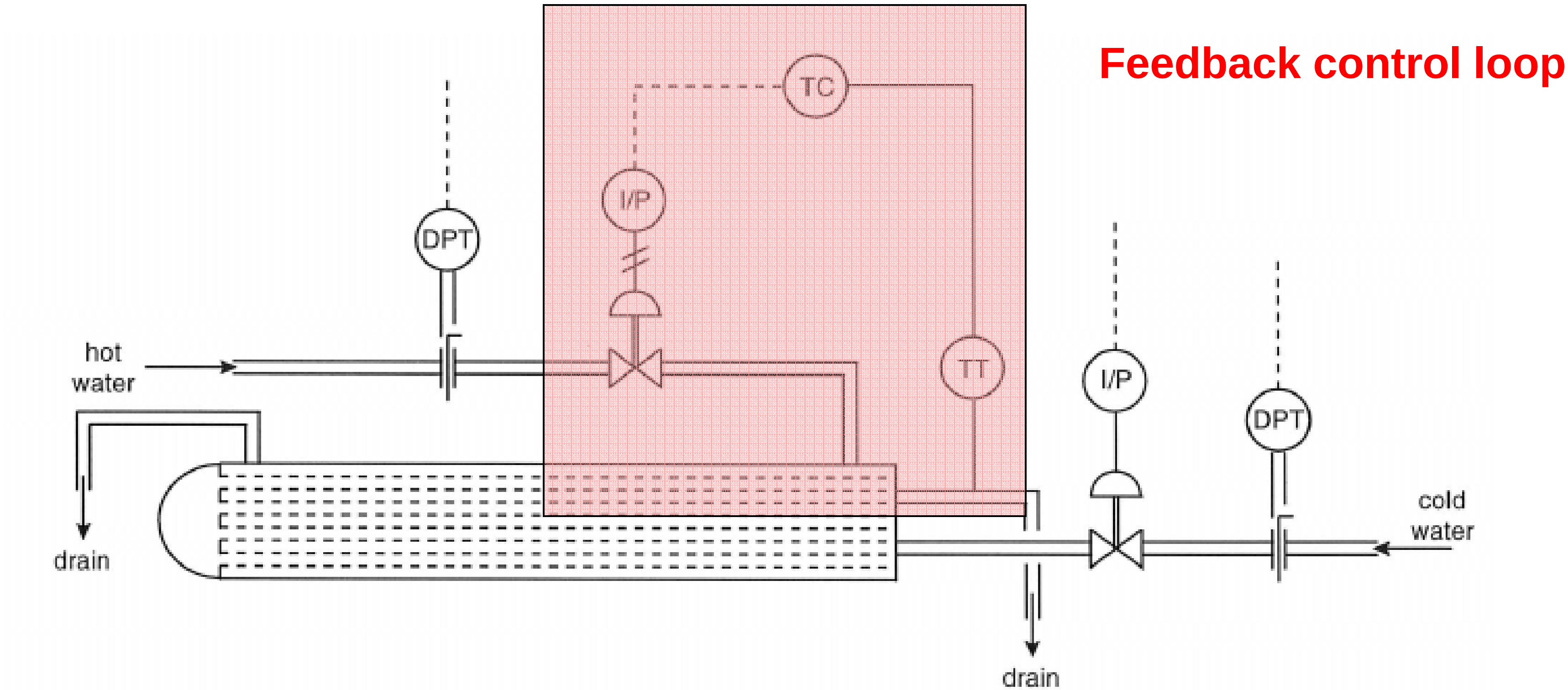
1. An **identifiable disturbance** is affecting significantly the measured variable, in spite of the attempts of a feedback control system to regulate these effects, and
2. This disturbance can be **measured,** perhaps with the addition of instrumentation.

Also, we would be interesting in controlling the source of the disturbance locally, before it affects our main process, if that were possible. If it is possible, we would usually implement cascade control, not feedforward control.

Examples of Feedforward Control

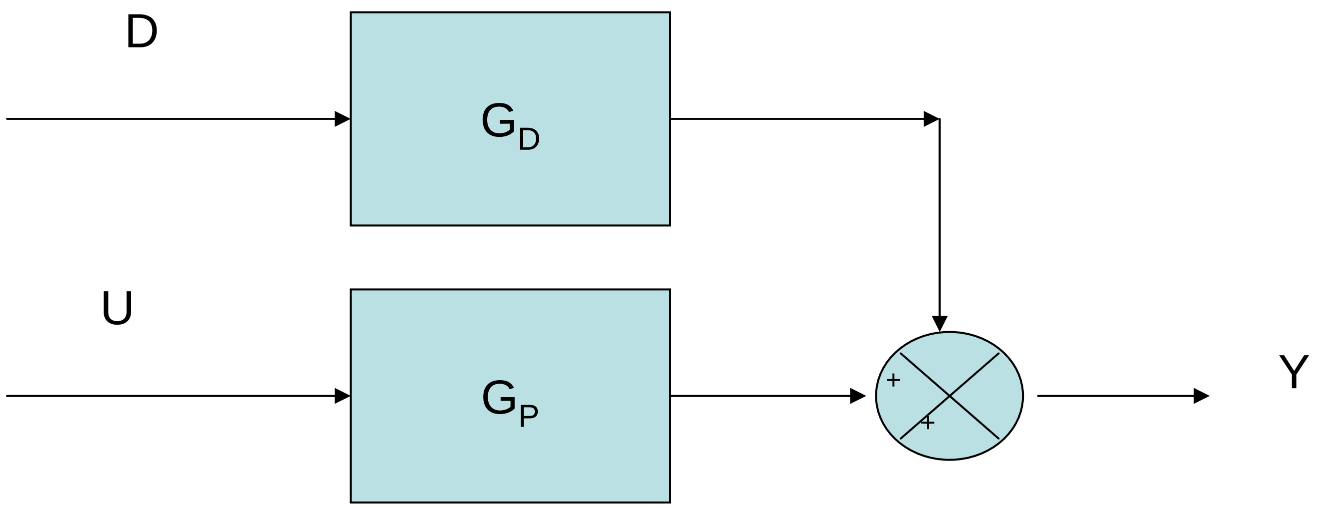
- **Shower**
  - Hear toilet flush (measurement)
  - Adjust water to compensate
  - Feedback is when you wait for the water to turn hot before changing the setting
- **Car approaching hill**
  - See how steep the hill is (measurement)
  - Push on pedal to keep steady speed
  - Feedback is to wait for slowing before adjusting pedal
- **Chemical system**
  - Measure something in feed stream
    - like $T_{water,return}$ in heating plant
  - Change heat to reactor

Example



- Goal: Cool down hot water with cold water stream
- Controlled & measured variable: T_{out}
- Manipulated variable: flow rate of hot stream (q_{hot})

Portion of Block Diagram



How do we manipulate U(s) to cancel the effect that D(s) will have on Y(s)?

Derivation

1. Write an algebraic equation for the block diagram

   $Y(s) = D(s) \cdot G_d(s) + U(s) \cdot G_p(s)$

2. If Y(s) is to be unaffected by D(s), then we want Y(s) = 0

3. Solve for U(s) in terms of D(s)

   $U(s) = [-G_d(s)/G_p(s)] \cdot D(s)$

   So $G_{ff} = -G_d(s)/G_p(s)$

If G_d and G_p are first order

$$G_p(s) = \frac{K_p e^{-\theta_p s}}{\tau_p s + 1} \qquad G_d(s) = \frac{K_d e^{-\theta_d s}}{\tau_d s + 1}$$

Therefore,

$$G_{ff}(s) = -\frac{\left(\dfrac{K_d e^{-\theta_d s}}{\tau_d s + 1}\right)}{\left(\dfrac{K_p e^{-\theta_p s}}{\tau_p s + 1}\right)} = -\frac{K_d}{K_p}\frac{\tau_p s + 1}{\tau_d s + 1} e^{-(\theta_d - \theta_p)s}$$

dynamic

$$= -\frac{K_d}{K_p}$$

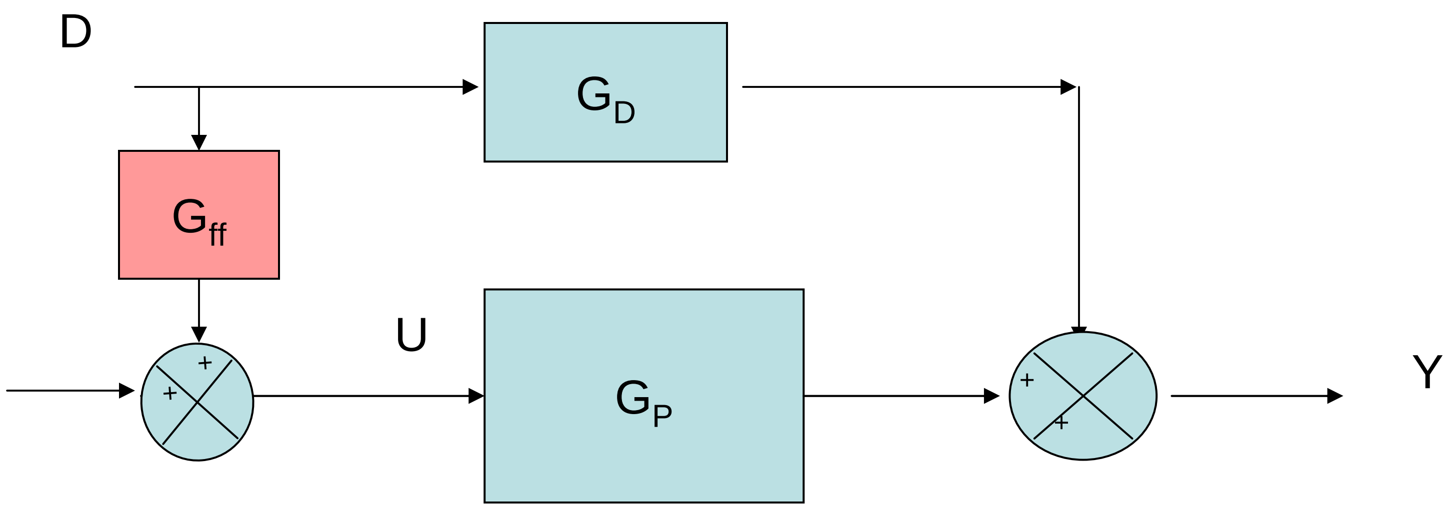
static

When is G_{ff} not feasible?

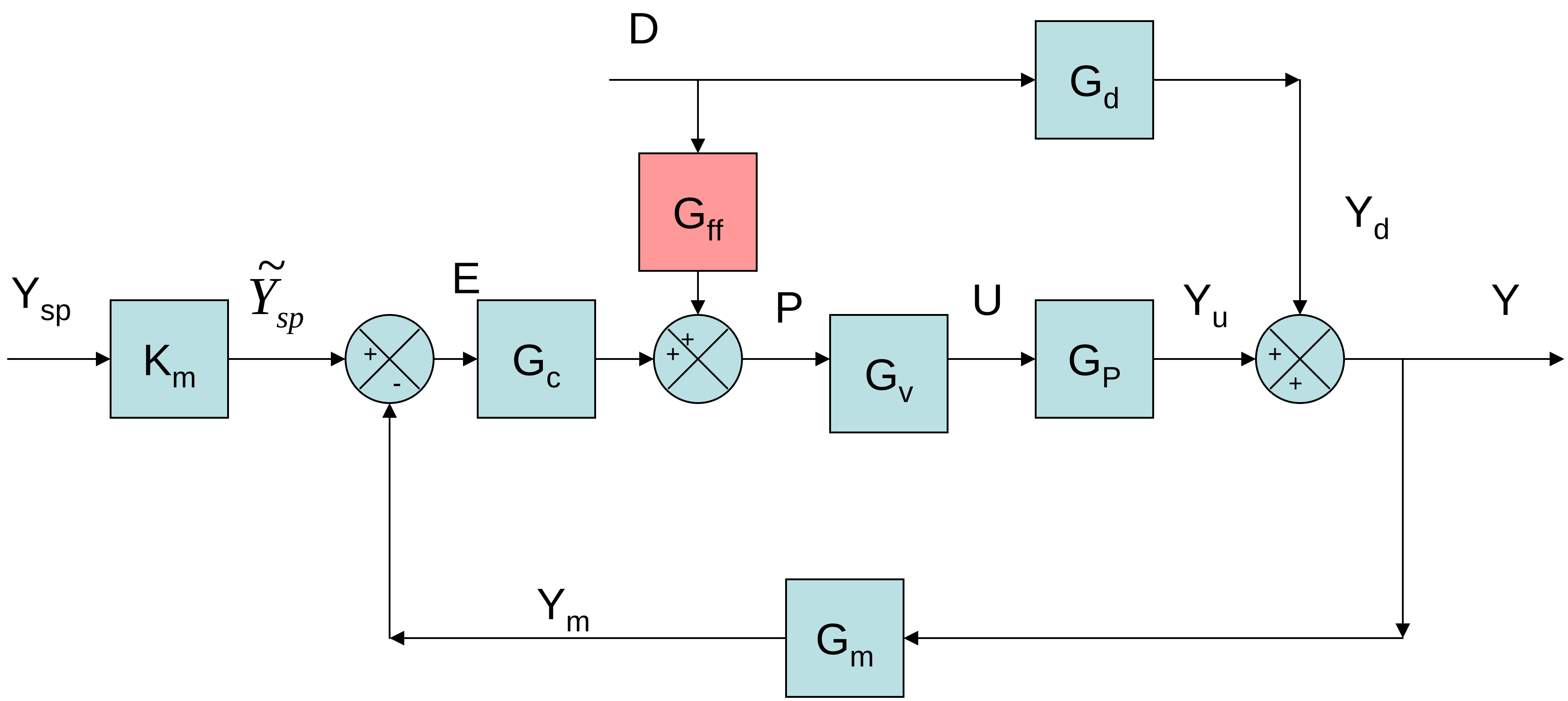
$$G_{ff}(s) = -\frac{K_d}{K_p}\frac{\tau_p s + 1}{\tau_d s + 1} e^{-(\theta_d - \theta_p)s}$$

When $\theta_p > \theta_d$, the function will grow without bounds

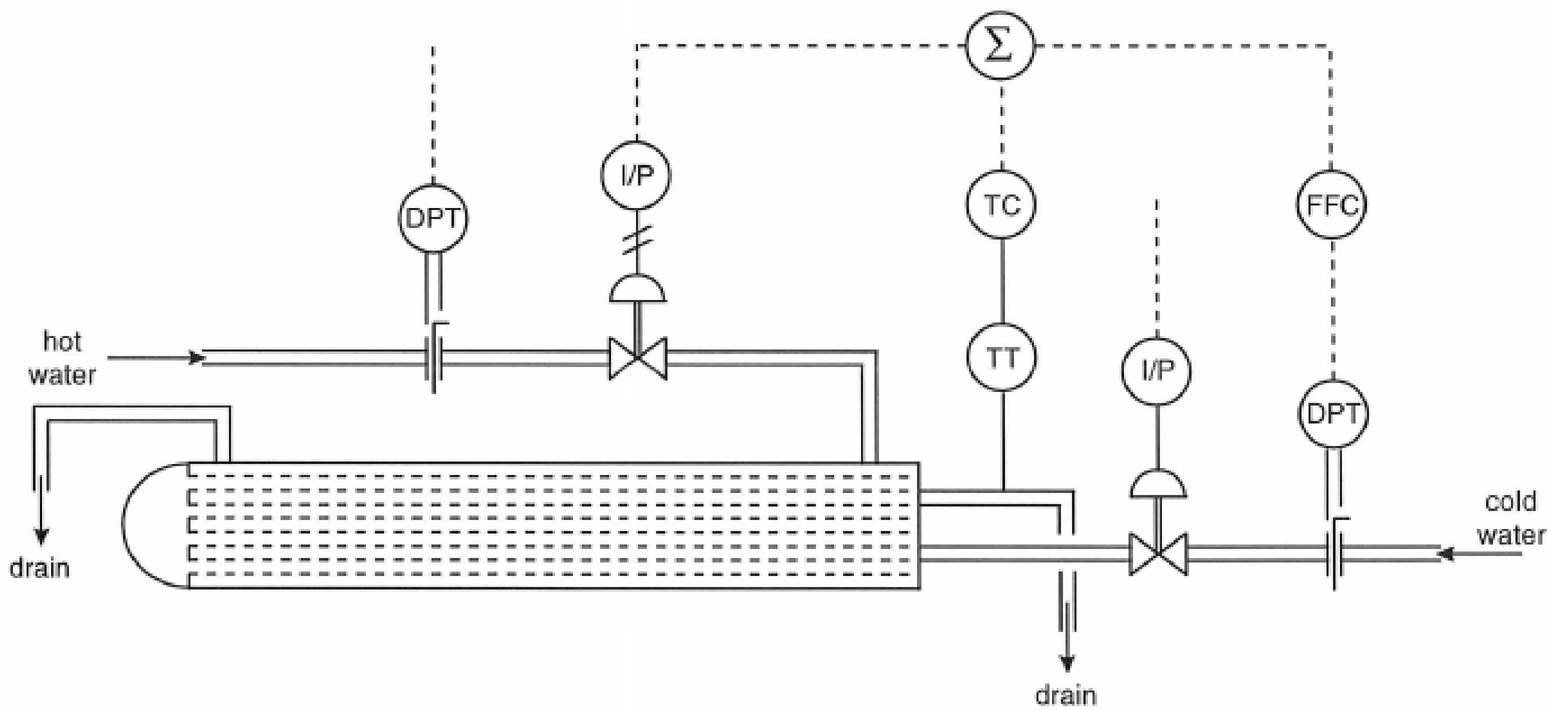
Modify block diagram



Feed Forward with Feedback Trim



Back to equipment diagram



- Measure the disturbance (fluctuating cold water inlet flow rate)
- Adjust controller through model (G_{ff})

Seborg's version

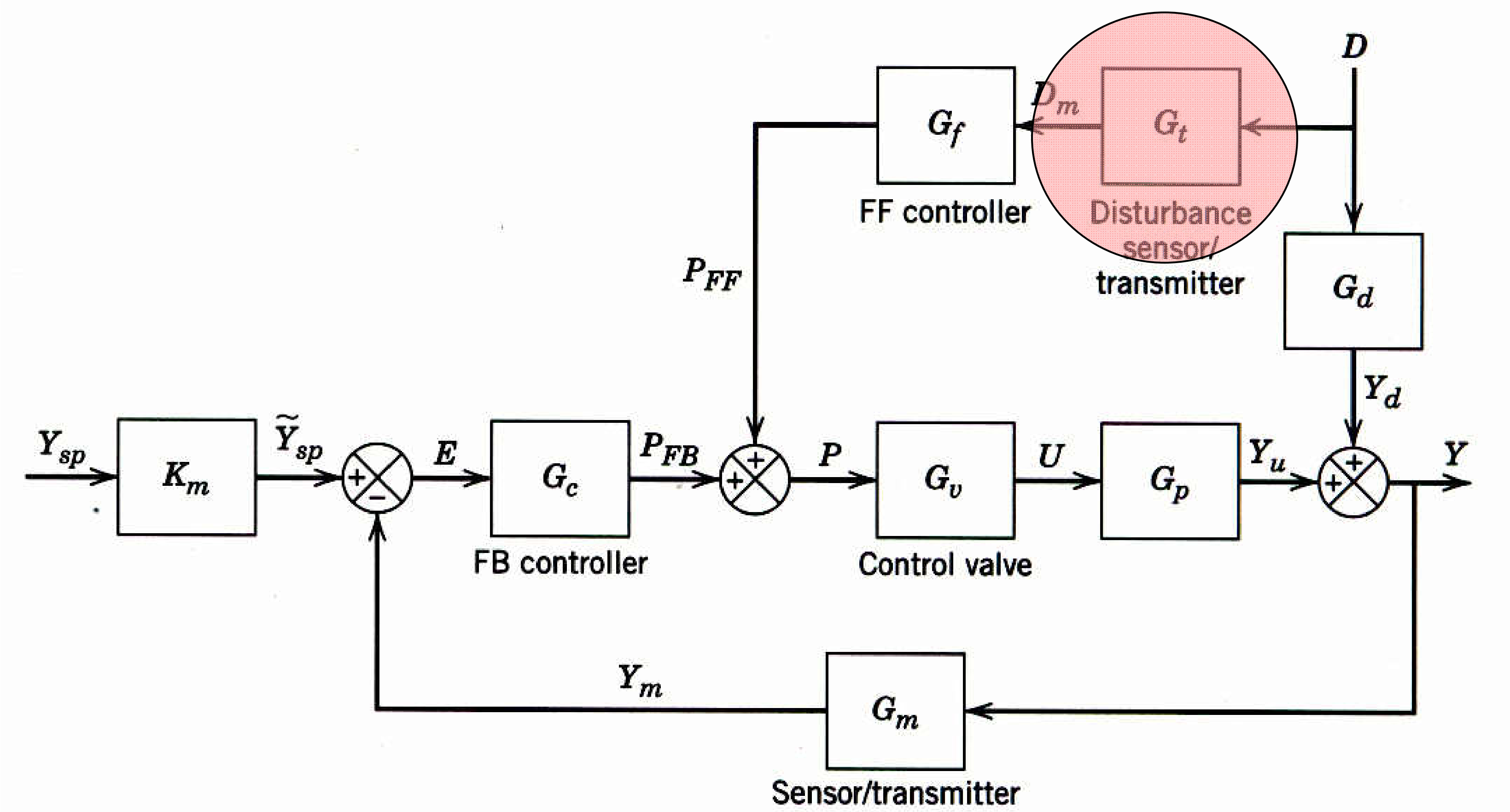
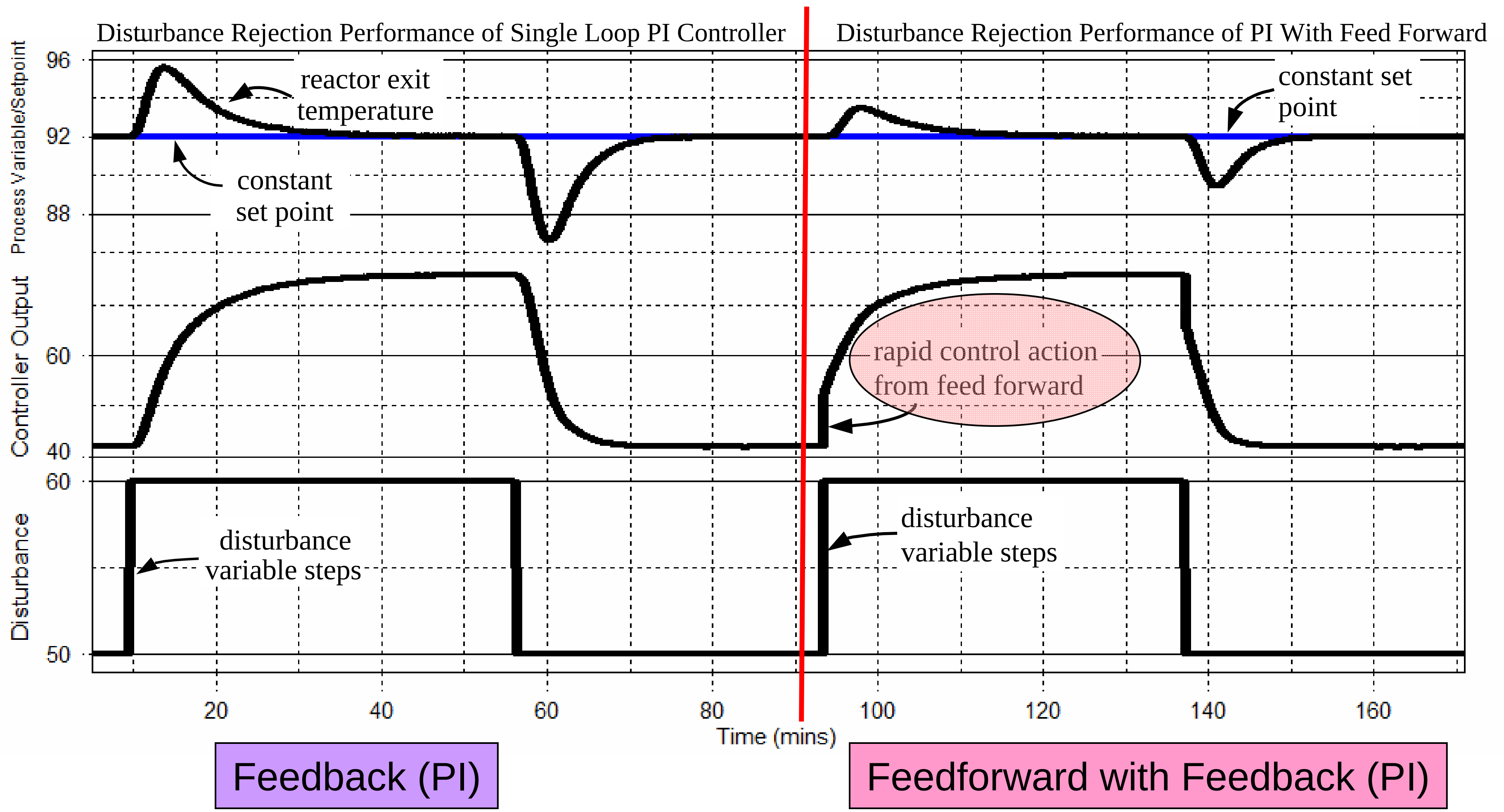


Figure 15.11

Disturbance Rejection Performance



Practice

$$G_p(s) = \frac{0.6e^{-37s}}{39s+1} \qquad G_d(s) = \frac{0.25e^{-57s}}{31s+1}$$

$$\frac{K_d}{K_p} = \frac{0.25}{0.60} = 0.417$$

$$\theta_d - \theta_p = 57 - 37 = 20$$

$$G_{ff} = -0.417\frac{39s+1}{31s+1}e^{-20s}$$

Physically Realizable G_{ff}

1. The exponential term must be negative
   - $\theta_p < \theta_d$

2. The order of the numerator must be less than or equal to that of the denominator

$$\frac{(s+1)(s+2)(s+3)}{(s+4)(s+5)}$$

Physically unrealizable

$$\frac{(s+1)(s+3)}{(s+4)(s+5)}$$

Physically realizable

$$\frac{(s+1)(s+3)}{s^3+s^2+s+1}$$

Physically realizable

Comparison of Feedforward & Cascade

	Cascade	**Feedforward**
Sensors	2	2
Controllers	2	1
Valve	1	1
Model	0	1
Restrictions	$t_{settling}$ small for inner loop	$\theta_p < \theta_d$

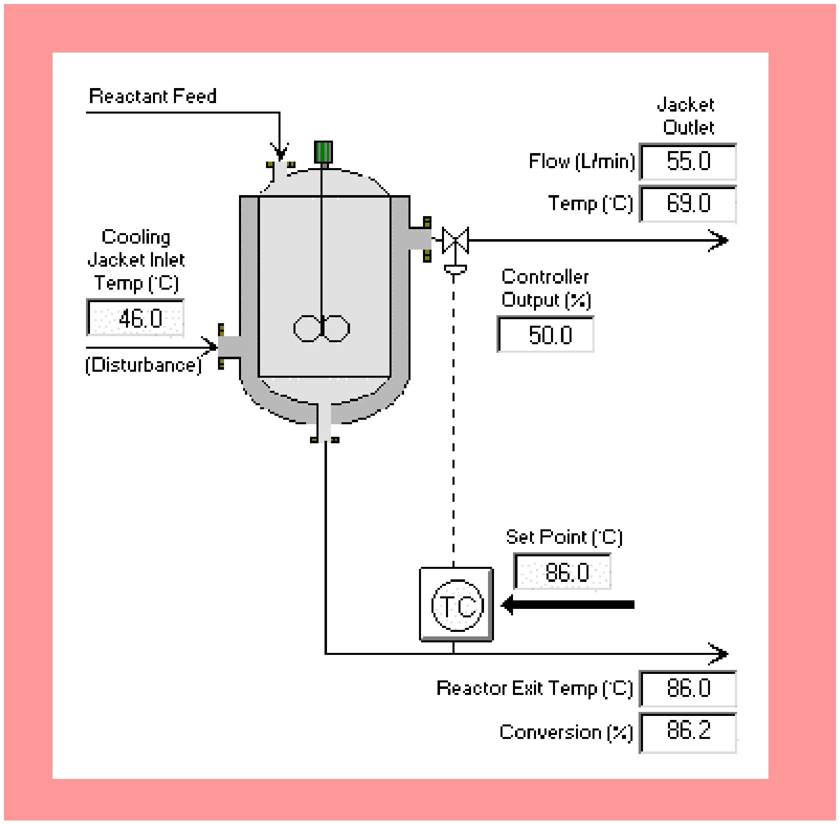
Recommendation

- Use cascade first
- Use feedforward when
  - Disturbance can be isolated
  - There is no “inner loop” variable that responds to the manipulated variable
  - Cannot use the same valve to control the disturbance

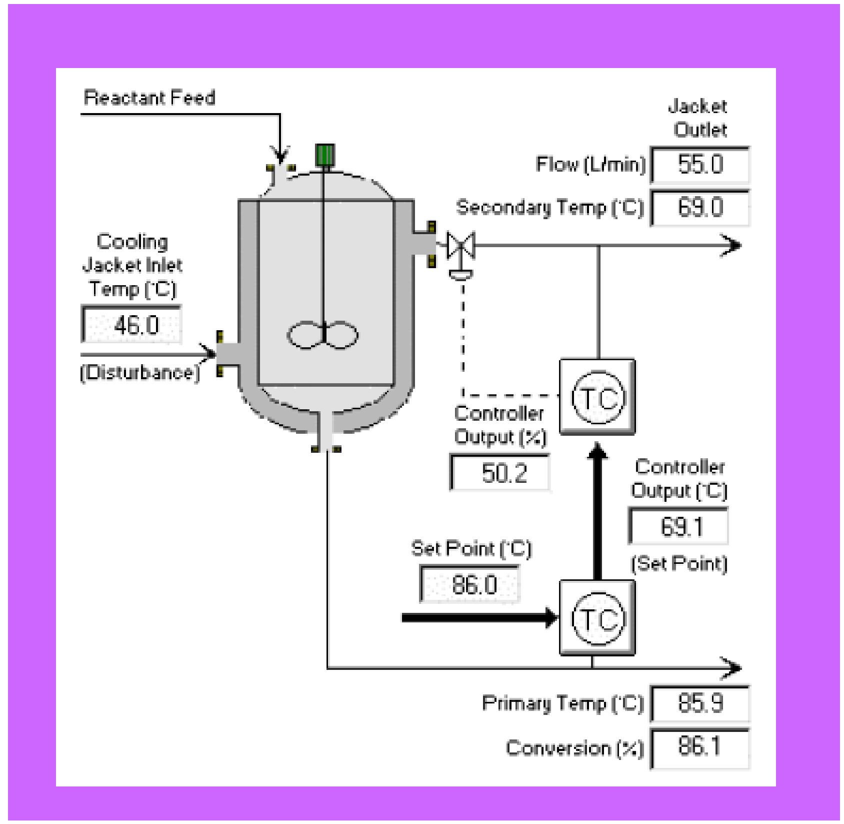
Feed Forward vs Cascade

Jacketed Reactor

FeedForward with Feedback



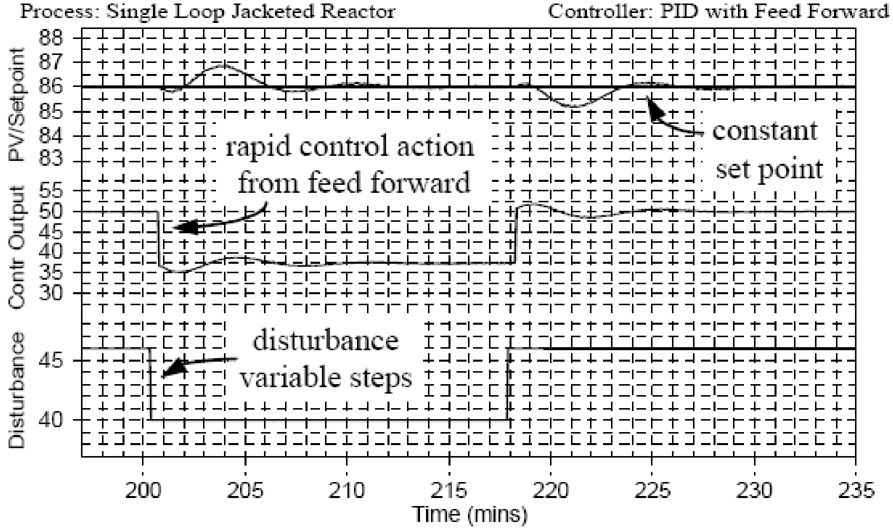
Cascade



Feed Forward vs Cascade

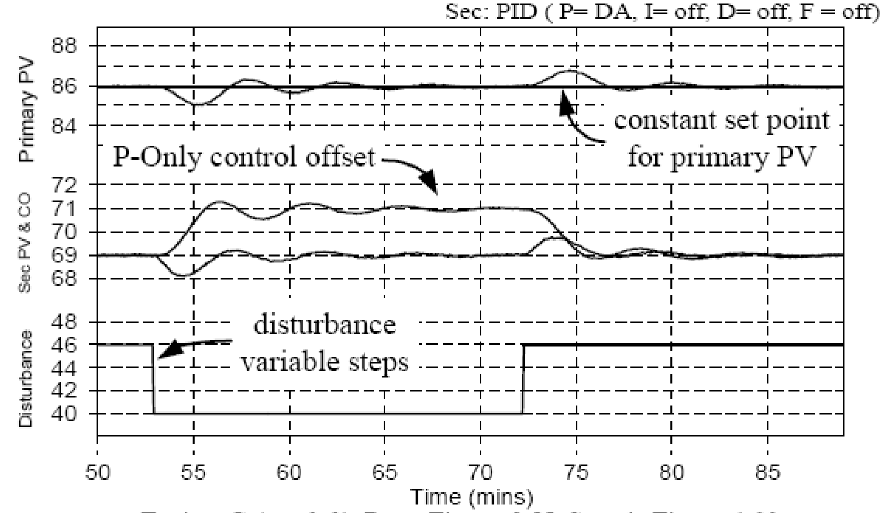
Jacketed Reactor

FeedForward with Feedback



Tuning: Gain = -2.70, Reset Time = 1.60, Deriv Time = 0.0, Sample Time = 1.00
Process Model: Gain(Kp) = -0.36, T1 = 1.58, T2 = 0.0, TD = 0.88, TL = 0.0
Disturbance Model: Gain(Kd) = 0.95, T1 = 1.92, T2 = 0.0, TD = 1.30, TL = 0.0

Cascade

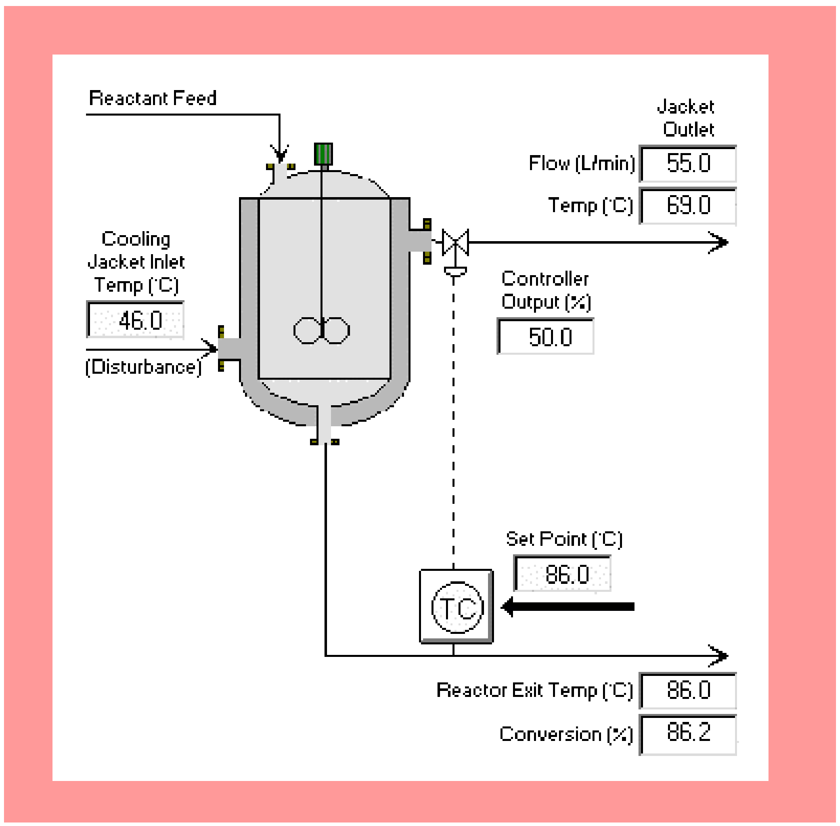


Tuning: Gain = 0.61, Reset Time = 0.55, Sample Time = 1.00

Tuning: Gain = -6.40, Sample Time = 1.00

Control Station Example

Jacketed Reactor



Volunteer needed