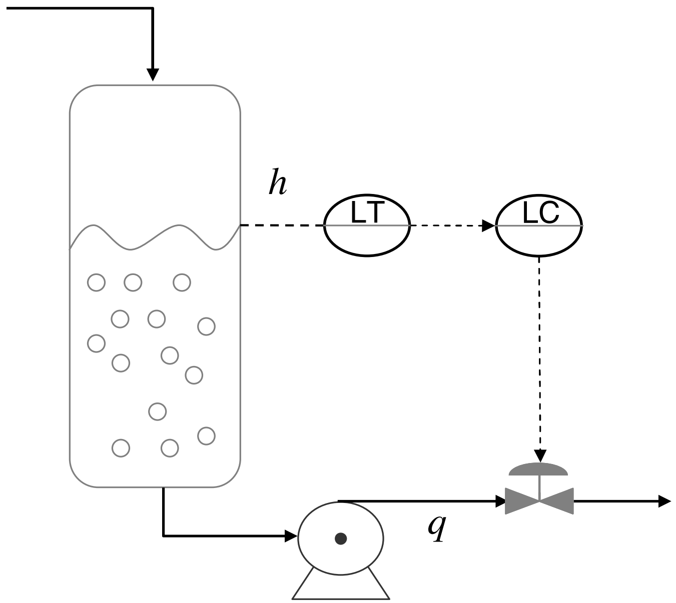
458.308 Process Control & Design

Lecture 5: Feedback Control System (Part 1)



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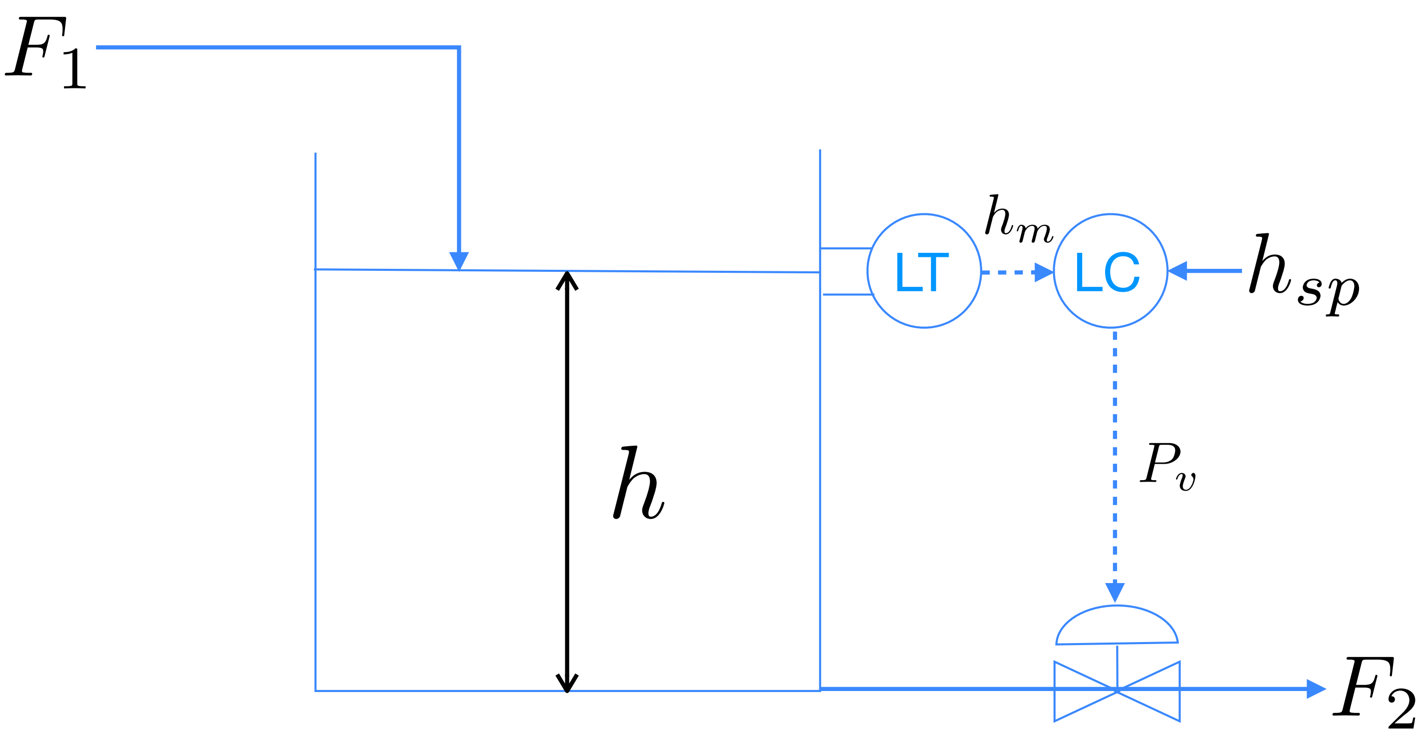
Feedback Control Scheme: Surge Tank



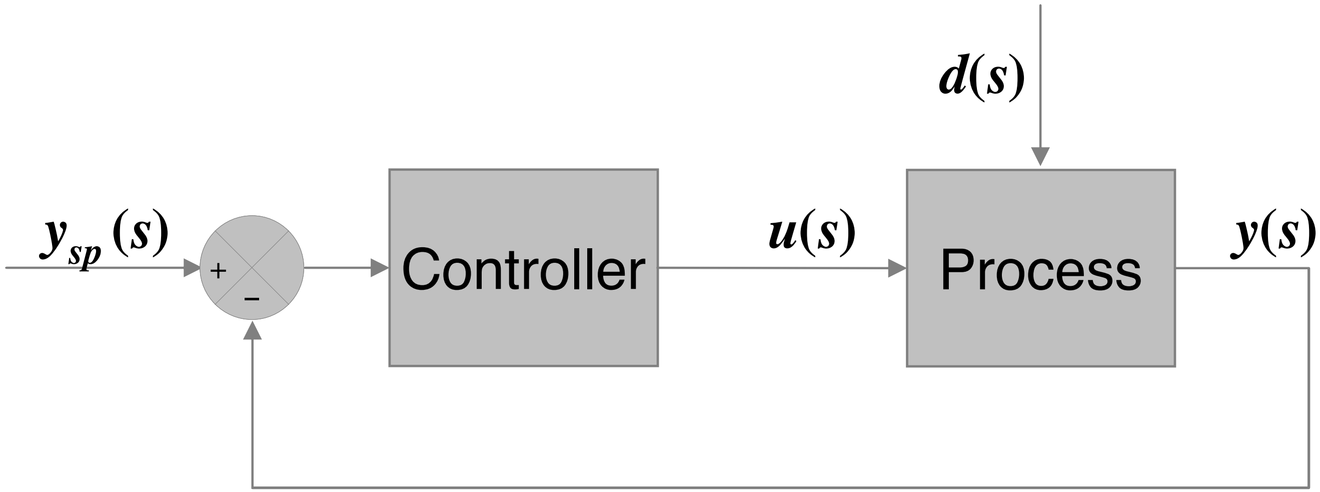
LT : a level measurement device (e.g., differential pressure cell)

- senses the level
- sends a signal to the controller

LC : a level controller

- compares the tank height (h_m) with the desired set point (h_{sp})
- sends a controller output (pressure signal) to the valve

Simplified Control Block Diagram



Negative feedback: self-stabilizing property with positive process gain

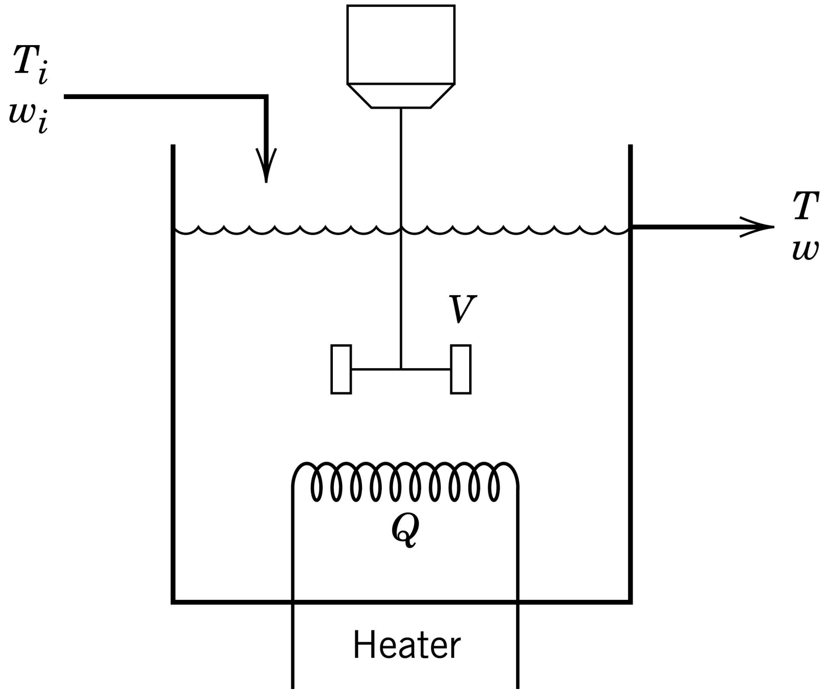
$$e = y_{sp} - y$$

Positive feedback: makes a process unstable with positive process gain in general

$$e = y_{sp} + y$$

Used for describing complex systems (i.e., biological system)

Block Diagram



$w_i = w$: no need for MB

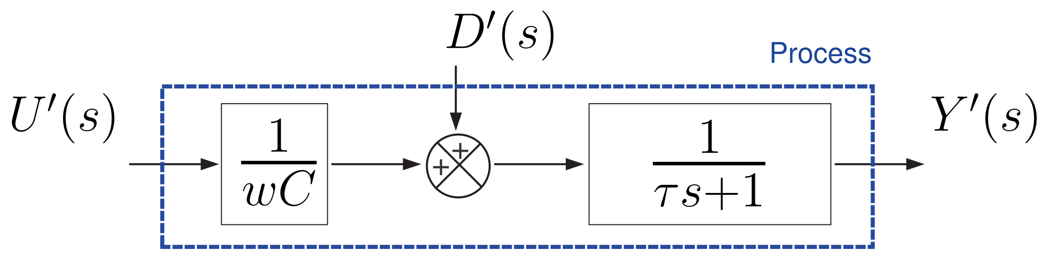
$$\frac{dT}{dt} = \frac{w_i}{V\rho}(T_i - T) + \frac{Q}{\rho V C_p}$$

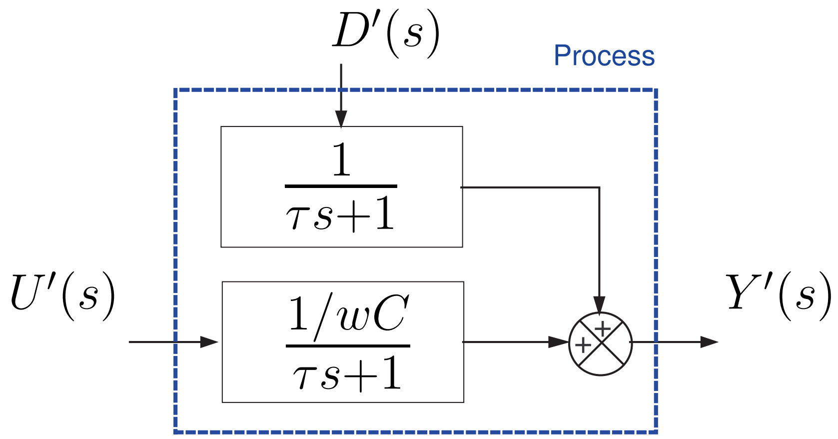
$$\Rightarrow \quad \tau \frac{dT}{dt} = (T_i - T) + \frac{Q}{wC_p}$$

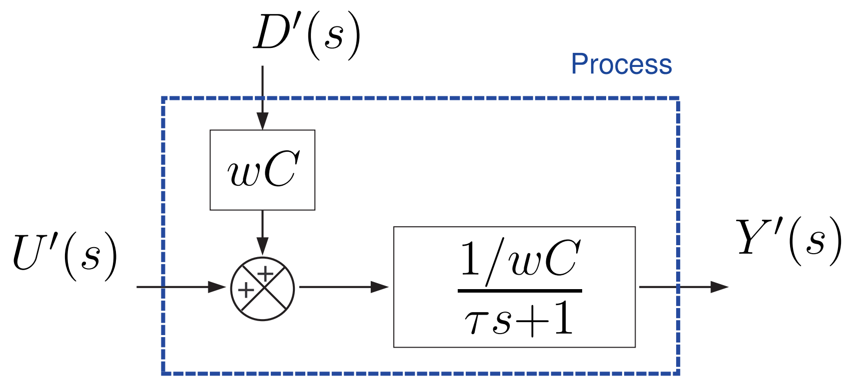
$$y' = T - \bar{T}, \; u' = Q - \bar{Q}, \; d' = T_i - \bar{T}_i$$

$$Y'(s) = \frac{1}{\tau s + 1}\left(\frac{U'(s)}{wC_p} + D'(s)\right)$$

Equivalent Representations







Pneumatic Control Valve

- Air is the energy source to move the valve stem
- Typical pressure range: (   ) -(   ) psig
- If the control signal is lost, then the valve stem will go to 3 psig

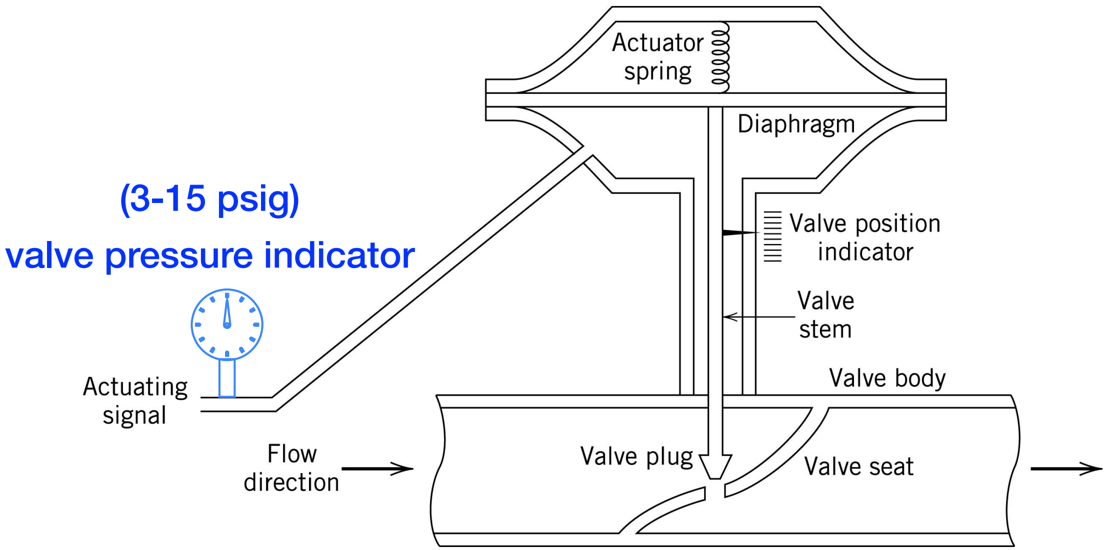


Figure 9.9 A control valve with a pneumatic actuator (air-to-open)

Types of Pneumatic Control Valve

1. Air-to-Open Valve (A-O)

Requires air to open the valve

Loss of air = ____________

Often referred to as __________ (F-C)

Choice of valve types?

__________ consideration

2. Air-to-Close Valve (A-C)

Requires air to close the valve

Loss of air = ____________

Often referred to as __________ (F-O)

If you control the reactor temperature by manipulating the steam flow rate into the reactor jacket, what type of control valve should you choose?

(a) A-O

(b) A-C

(c) F-O

(d) F-C

If we consider the control valve as an input-output system, what are the input and output variables?

(a) feedback error, pneumatic pressure

(b) pneumatic pressure, steam flow rate

(c) steam flow rate, temperature

(d) temperature, set point

Actuators are also categorized as ‘direct acting’ or ‘reverse acting’ In a **direct acting** actuator, an *increase* in pneumatic pressure applied to the diaphragm *extends* the valve stem. In a **reverse acting** actuator, an *increase* in pneumatic pressure applied to the diaphragm *lifts* the valve stem. Which of the following statements is (are) correct?

- Air-to-Open valve is direct acting.
- Air-to-Close valve is direct acting.
- The gain of the control valve (Kv) will be positive for a reverse acting actuator
- The gain of the control valve (Kv) will be negative for a direct acting actuator

Algorithm: On/Off Controller

How does the controller change the flow rate?

① $y_m (= h_m) > y_{sp}$: valve is ______ open

$y_m < y_{sp}$: valve is ______ closed

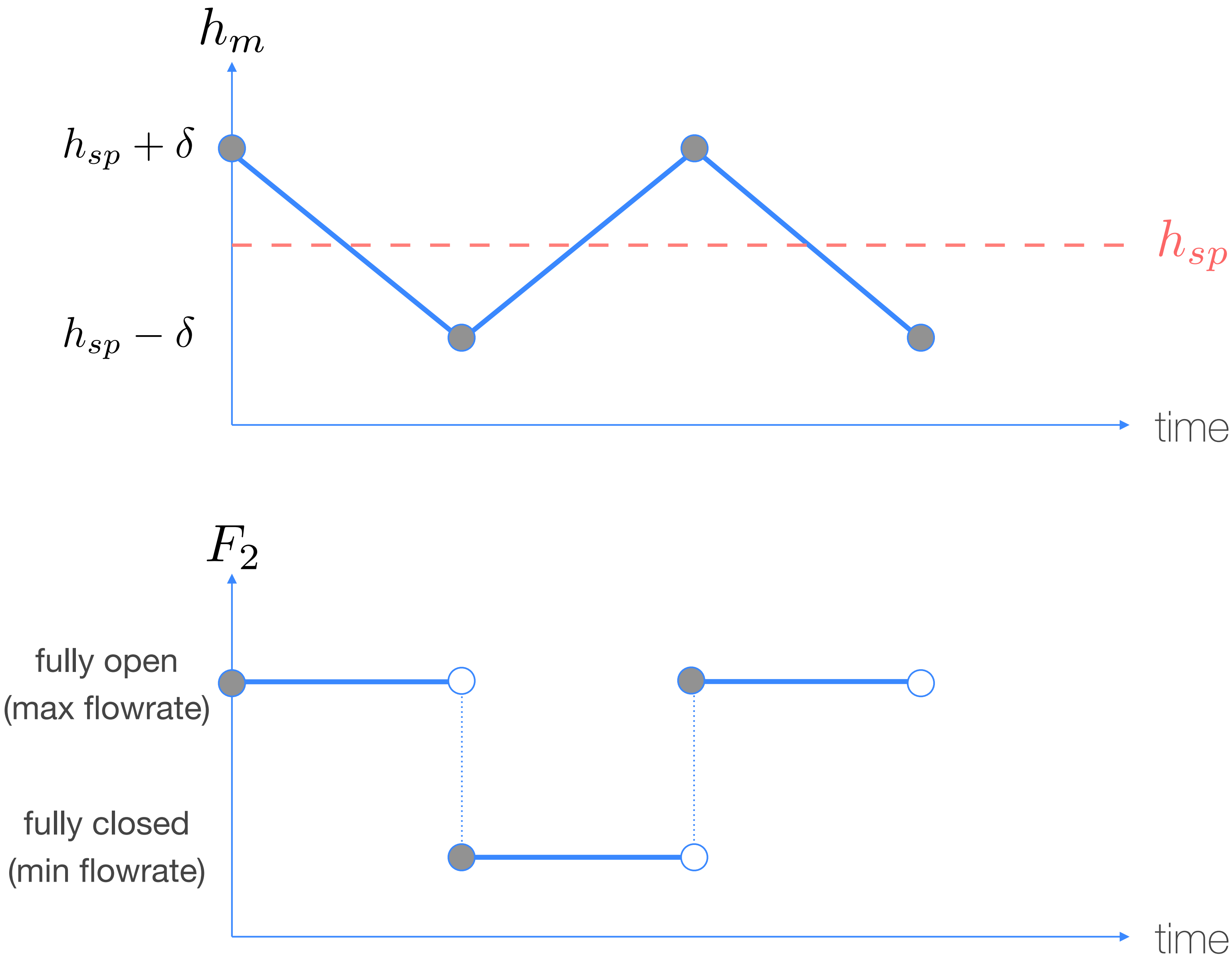
Example) Home heating unit

② In practice, a dead-band (δ) is used

$y_m \geq y_{sp} + \delta$: valve is fully open

$y_m \leq y_{sp} - \delta$: valve is fully closed

$y_{sp} - \delta < y_m < y_{sp} + \delta$: current valve position


h_m
$h_{sp} + \delta$
$h_{sp} - \delta$
h_{sp}
time
F_2
fully open
(max flowrate)
fully closed
(min flowrate)
time

Algorithm: Proportional Controller

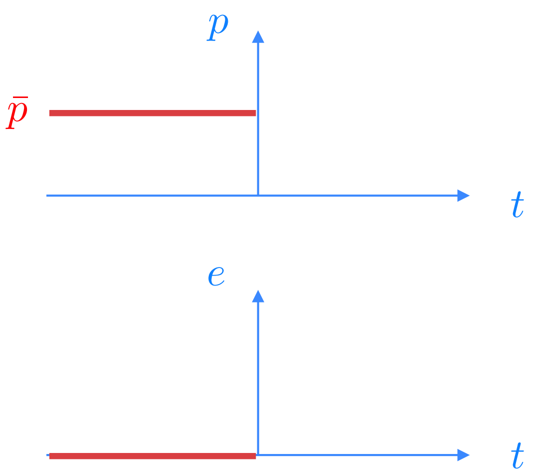
Control action is proportional to the feedback error

$$p(t) = \bar{p} + K_c(y_{sp}(t) - y_m(t)) \Rightarrow p'(t) = K_c e(t)$$

p : valve top pressure

K_c : proportional gain (tuning parameter)

$\bar{p}$: steady-state valve top pressure when $e(t) = y_{sp}(t) - y_m(t) = 0$



P-controller is static or memory-less

Proportional Band (PB) = $\dfrac{100}{K_c}\%$

(Foxboro, etc.)

Sign of Kc

This depends on the valve type

If e(t) > 0 $(y_{sp} > y_m)$; F_2 should be lower

If e(t) < 0 $(y_{sp} < y_m)$; F_2 should be higher

① Air-to-Open

$$e(t) > 0 \;\rightarrow\; F_2 \downarrow \;\rightarrow\; \text{valve close} \;\rightarrow\; \text{air pressure} \downarrow$$

$\therefore$ ________________

$$e(t) < 0 \;\rightarrow\; \text{same}$$

② Air-to-Close

$$e(t) > 0 \;\rightarrow\; \text{air} \uparrow \; \text{to close}$$

$\therefore$ ________________

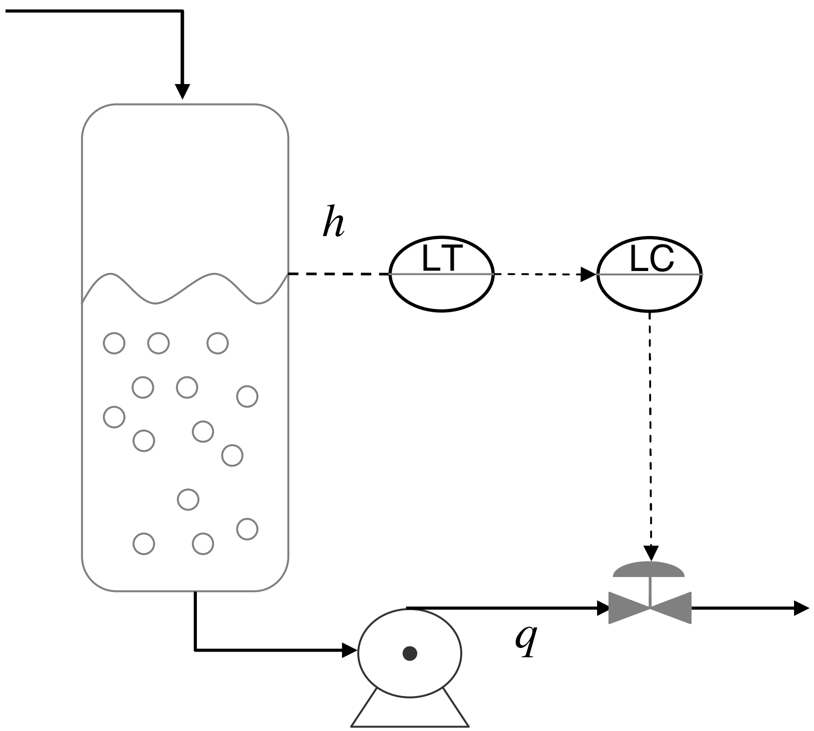
Reverse-Acting / Direct-Acting

Kc > 0 is called ____________-acting because

$$\text{as } y_m \uparrow, \quad p \downarrow$$

Kc < 0 is called ____________-acting because

$$\text{as } y_m \uparrow, \quad p \uparrow$$



LT is designed to be direct-acting (most transmitters are direct-acting)

- Its output signal increases as the level increases

P-Controller: Pros and Cons

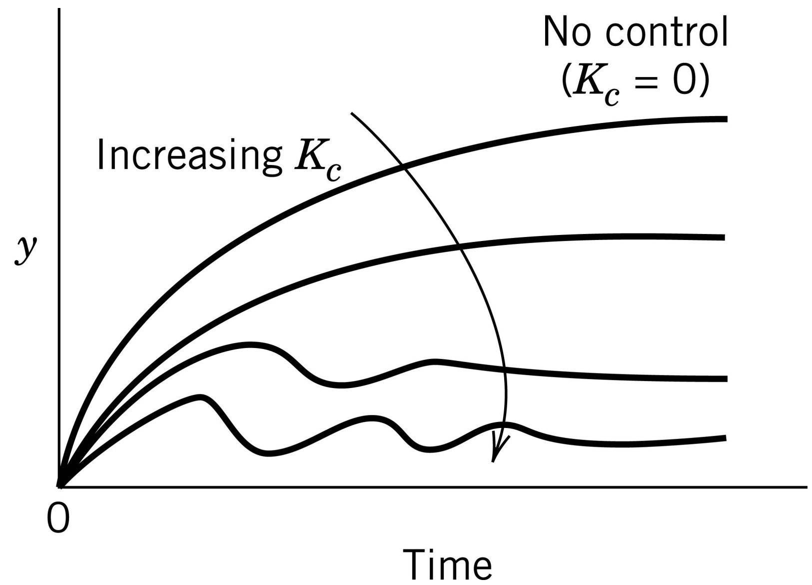
Advantage: simplicity

Disadvantage

Leaves offset with a set-point change or a sustained disturbance

why?

$\bar{p}$ is a equilibrium point (input) for the previous set point or disturbance



Algorithm: Proportional Integral (PI) Control

$$p(t) = \bar{p} + K_c\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t^*)dt^*\right)$$

τ_I : integral time or reset time (→∞ = P-control)

Integral control action: reset control, floating control

Some variations

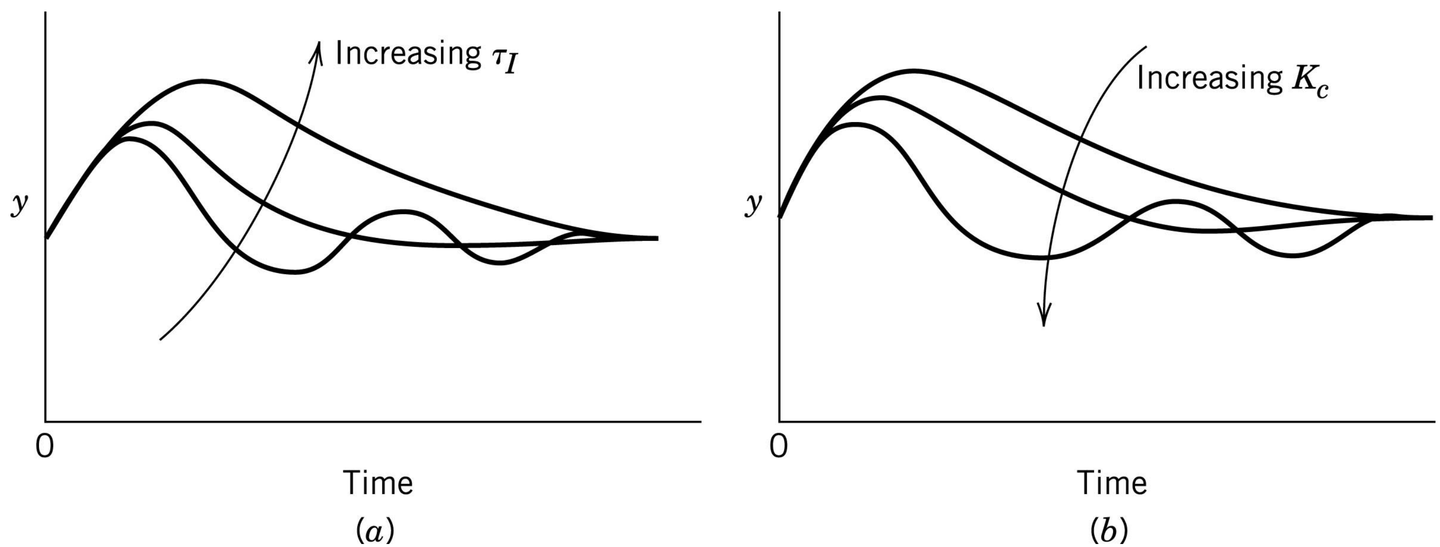
Honeywell $$p(t) = \bar{p} + K_c\left(e(t) + \tau_R\int_0^t e(t^*)dt^*\right)$$

Foxboro by Schneider Electric $$p(t) = \bar{p} + \frac{100}{PB}\left(e(t) + \tau_R\int_0^t e(t^*)dt^*\right)$$

τ_R : reset rate

PI-Controller: Pros and Cons

Advantage: eliminates __________ (regardless of size of Kc)



Disadvantages

One more parameter to tune

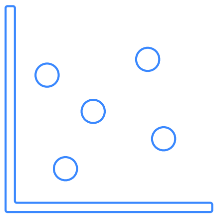
Easier to induce oscillation or instability

Algorithm: Proportional Integral Derivative (PID) Control

Adjustment proportional to the current error + accumulated error + current rate of change in the error

$$p(t) = \bar{p} + K_c \left(e(t) + \frac{1}{\tau_I} \int_0^t e(t^*) dt^* + \tau_D \frac{de}{dt} \right)$$

τ_D : derivative time constant



Pure differentiation in real-time is not possible since evaluation of de/dt at time t requires error information beyond time t. But it can be approximated very closely

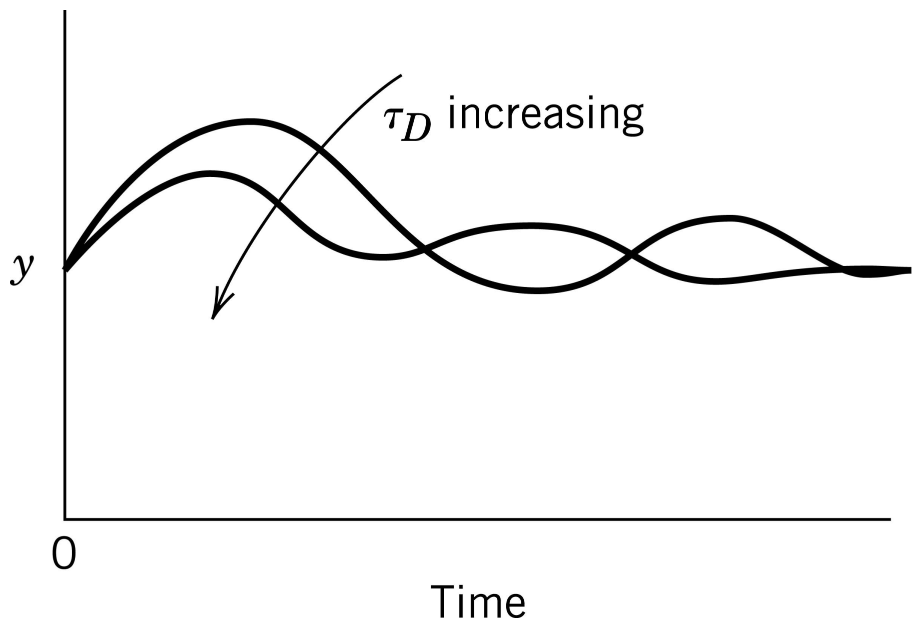
PID Controller: Pros and Cons

Advantages

Quick action to a change in the error - effective prevention of runaway (e.g., in an auto-catalytic reactor)

Decrease settling time for processes with slow dynamics and fast disturbances

Decrease ___________ (stabilizing factor for integral mode, etc.)

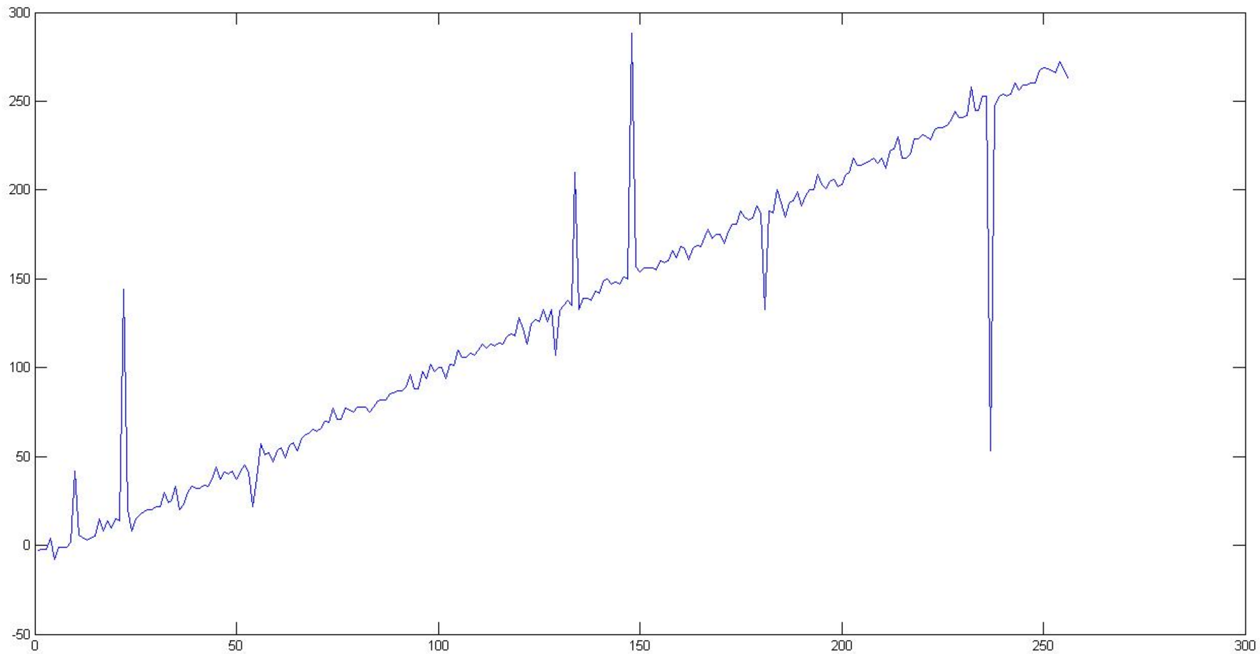


PID Controller: Pros and Cons

Disadvantages

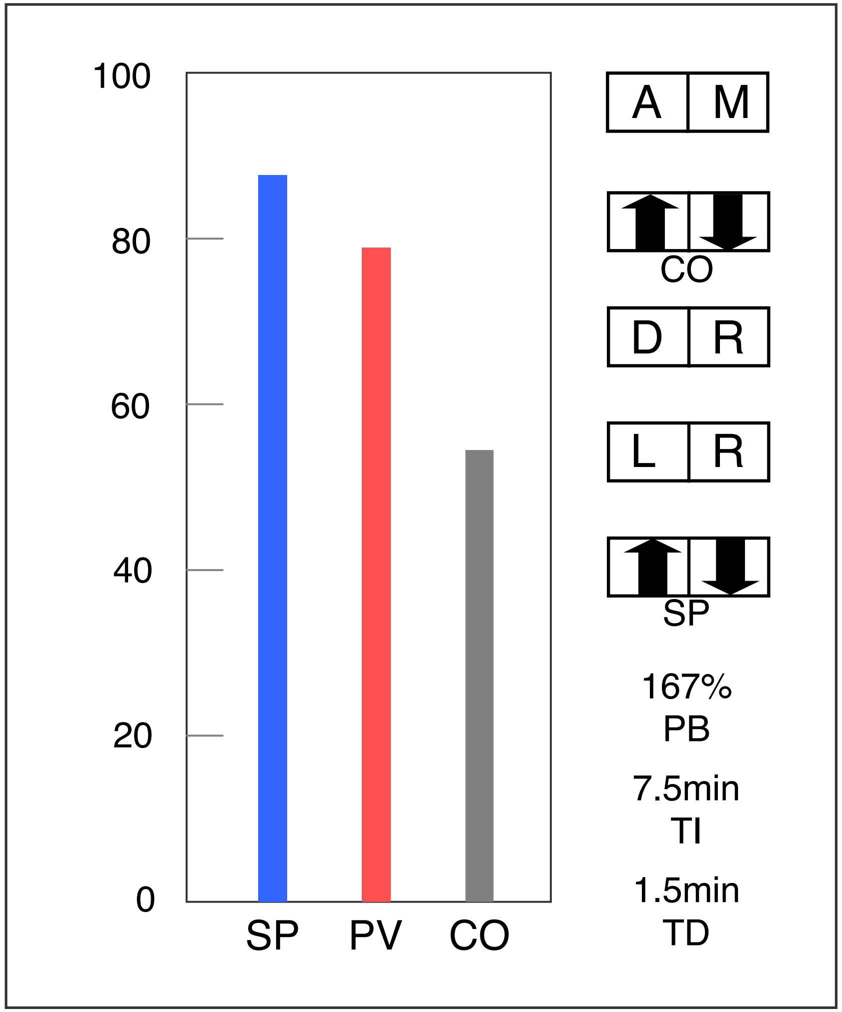
Yet one more parameter to tune

Amplifies measurement _____ effect (not suitable in flow control)



“noisy” measurements

Typical PID Controller Display



PV, SP, CO: Process variable, Set point, Control output (normalized 0-100%) CO is also denoted as OP.

Auto/Manual Switch (Bumpless Transfer)

Direct/Reverse Switch

Local/Remote Switch: source of set point signal

Digital PID Controller

Analog:

$$p(t) = \bar{p} + K_c \left(e(t) + \frac{1}{\tau_I} \int_0^t e(t^*) dt^* + \tau_D \frac{de}{dt} \right)$$

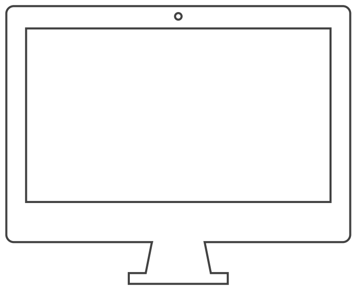
Digital:

$$p(t_k) = \bar{p} + K_c \left(e(t_k) + \frac{\Delta t}{\tau_I} \sum_{i=0}^{k} e(t_i) + \tau_D \frac{e(t_k) - e(t_{k-1})}{\Delta t} \right)$$

Δt : sampling period (interval)

$e(t_k)$: error at the k^{th} sample time

$p(t_k)$: controller output at the k^{th} sample time

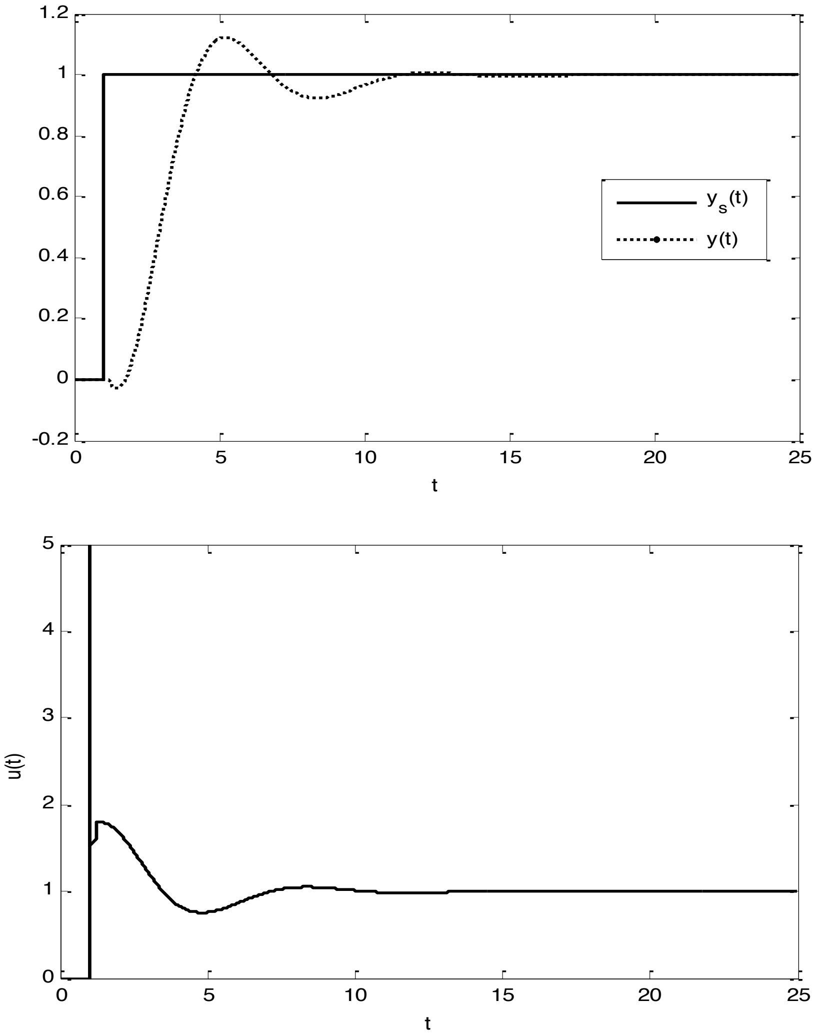


Removing "Kicks"

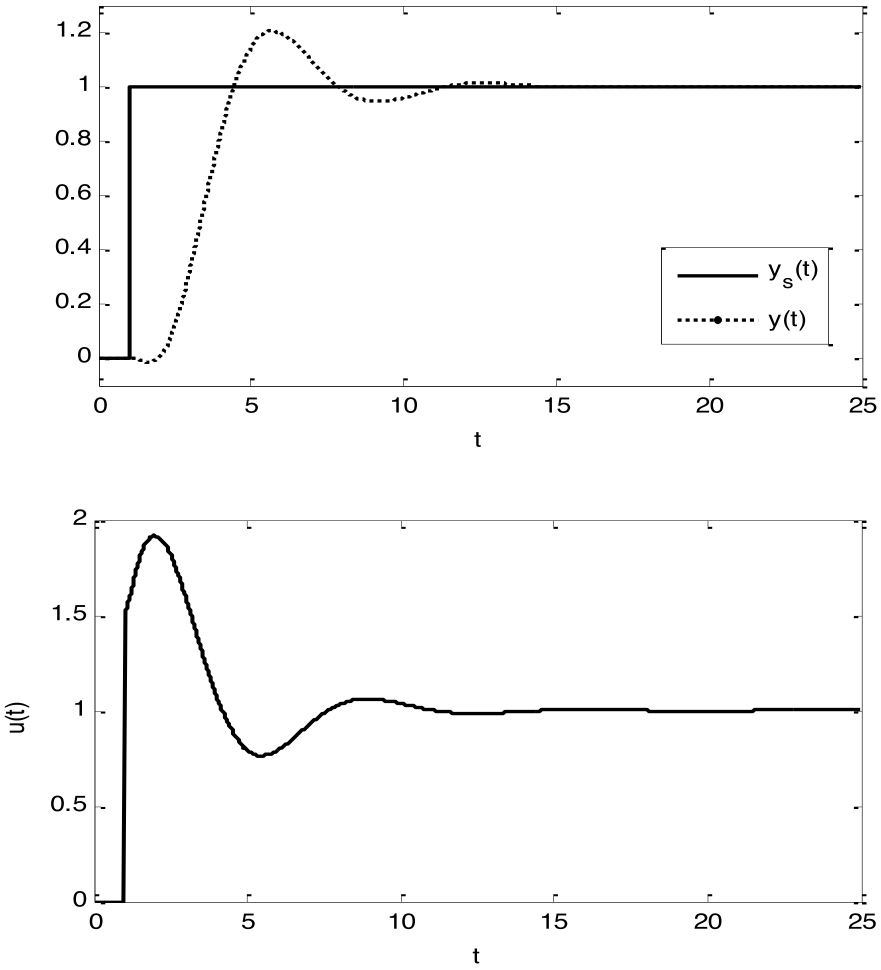
- Sudden set point change (a step change)
  - de/dt will be very large, giving a sudden jump in the valve position (undesirable in most cases)
  - Apply the derivative action only on the output signal, not set point signal

$$\frac{de}{dt} = \frac{d}{dt}\left(y_{sp}(t) - y_m(t)\right) \Rightarrow -\frac{dy_m}{dt}$$

- Similar phenomenon can show up for the P-mode, though not as severe as the D-mode



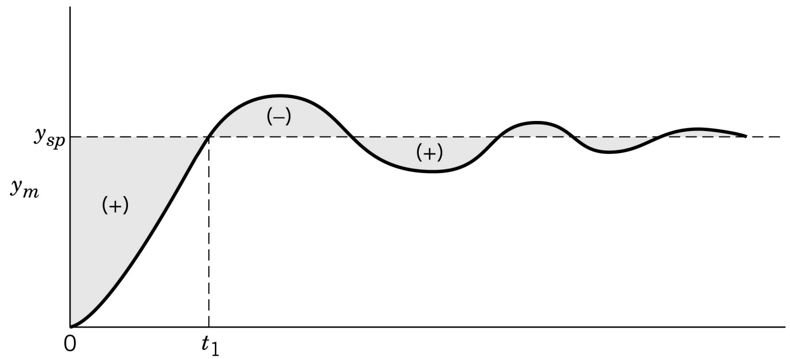
Without anti-derivative-kick

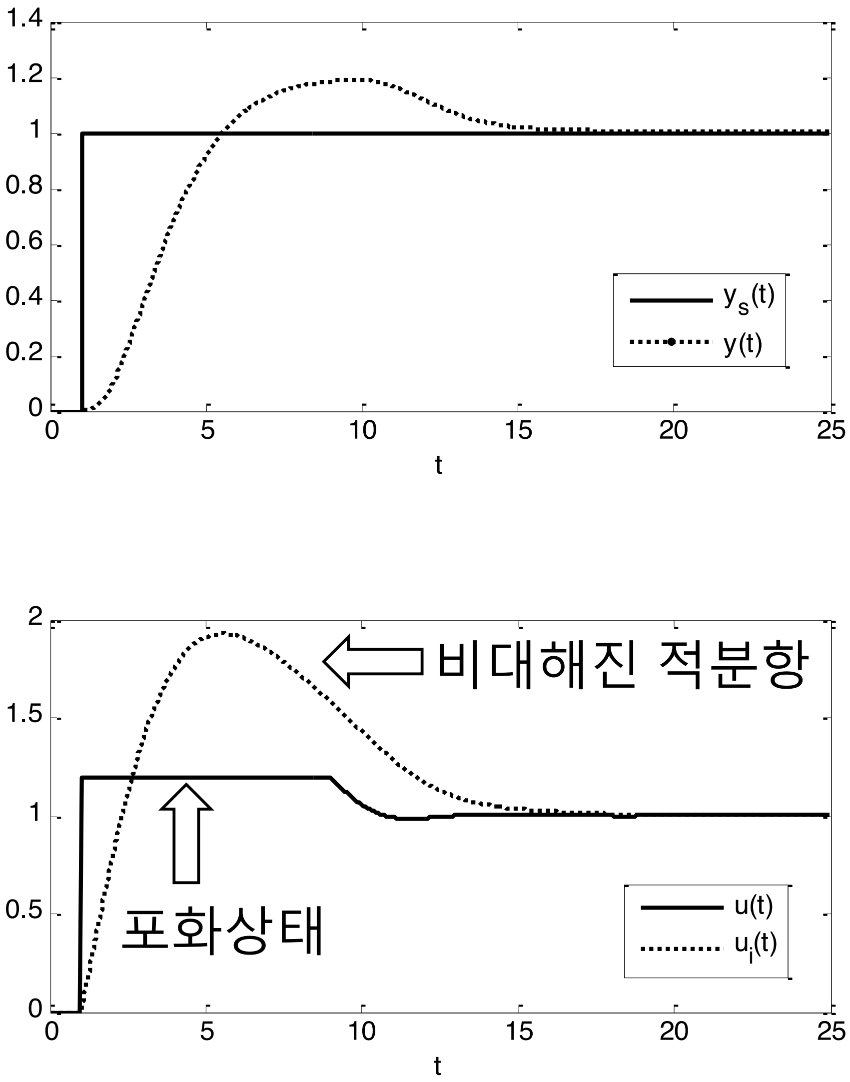


With anti-derivative-kick

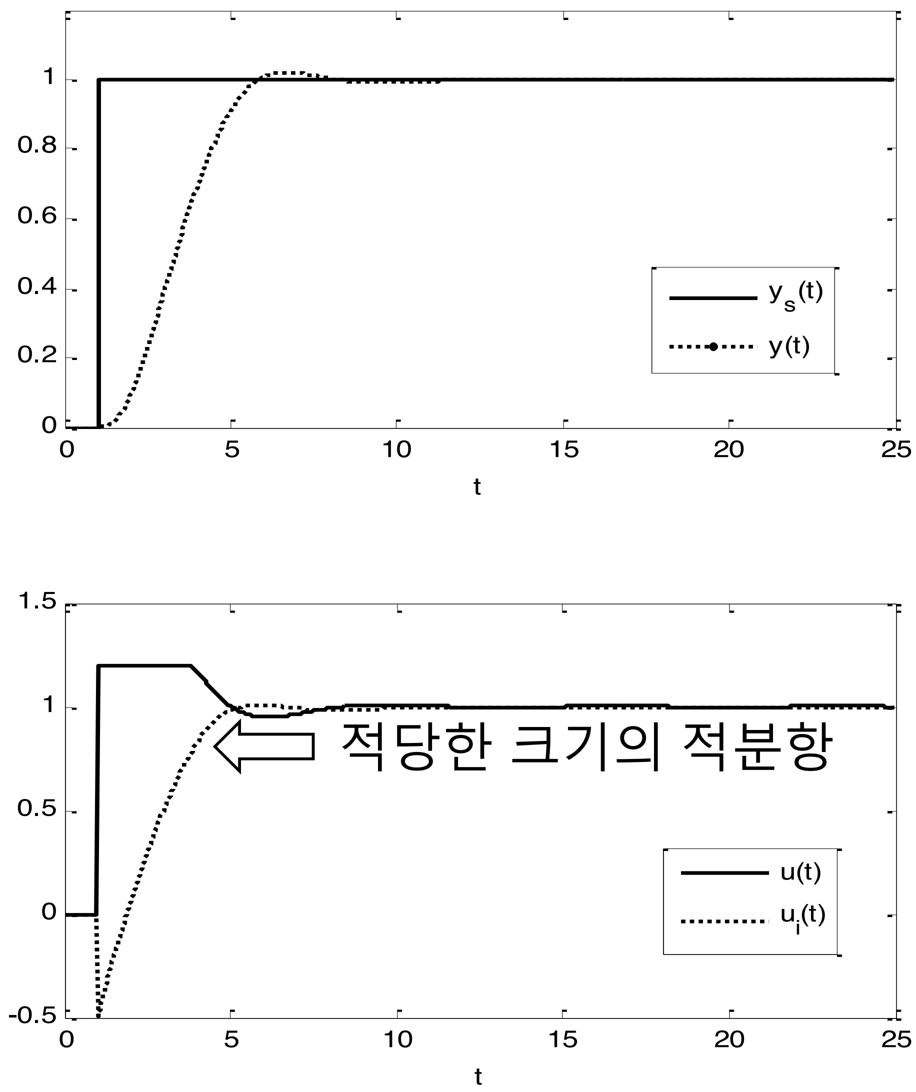
Windup and Anti-Windup

- Windup
  - When a constant error persists for a long time (such as when the valve saturates), the integral term can be wound up to a very large term
- Consequence
  - When the reason for the constant error (e.g., un-realizable set point change or too large a disturbance to reject completely) goes away, the integral term must unwind before the valve position returns to the normal value and control resumes
  - Large error in the opposite direction will result





Without anti-windup



With anti-windup(back-calculation)