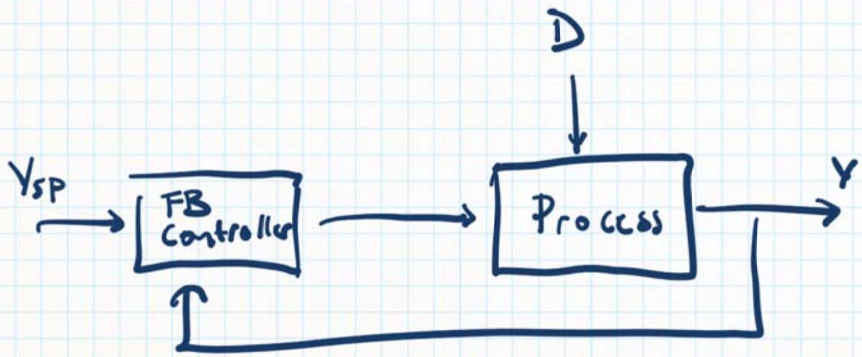
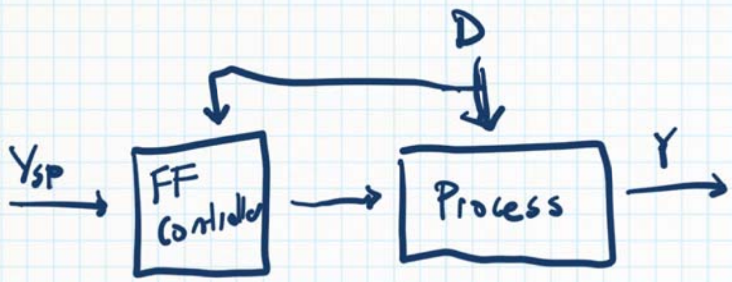
UNIT 3: Advanced Control System

Chp 15: feed forward + Ratio Control



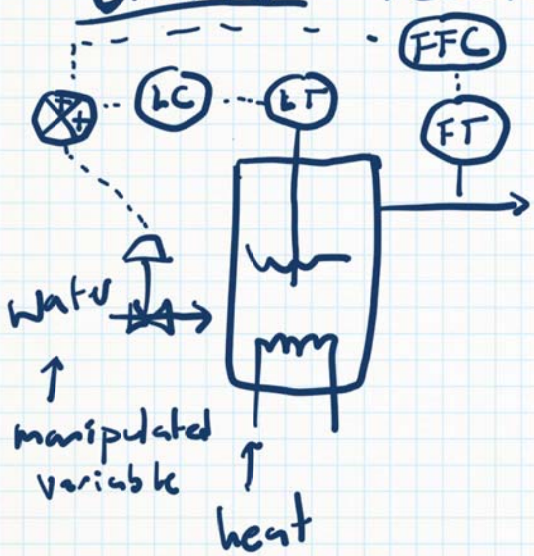


Feed back

(+)
- Corrective action occurs for <u>any</u> deviation input (regardless of source)
- Requires minimal knowledge about sys
- PID controllers are robust

(−)
- perfect control not possible
- <u>Cannot compensate for KNOWN disturbances</u> before they happen
- Not good for sys w/ large time constants
- CV is hard/impossible to measure online

Class 18 Feedforward Control → 'feedback trim'



→ Steam (disturbance variable)

Level : control variable

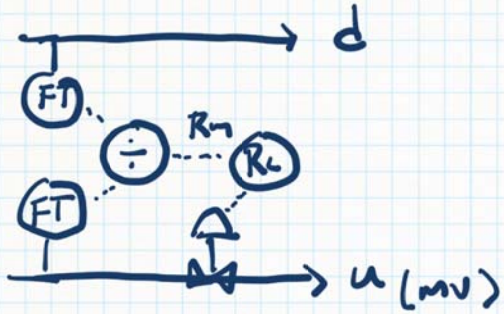
"Ratio Control" ← subset of feed forward

$$R = \frac{u}{d} \begin{array}{l} \leftarrow \text{manipulated variable} \\ \leftarrow \text{disturbance variable} \end{array}$$

flow rates

Example Systems

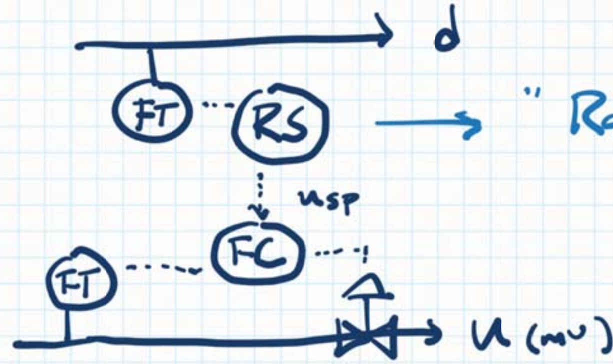
- Blending operation
- Stoichiometry in Reactors
- Reflux in Distillations
- furnace : fuel/air ratio



METHOD 1

process gain will change

$$K_p = \left(\frac{\delta R}{\delta u}\right)\Big|_d = \frac{1}{d}$$



"Ratio Station"

multiplies signal by an adjustable gain K_R

- output is the setpoint for the controller

METHOD 2

- Process Gain is constant

$$K_R = R_d \frac{S_d}{S_u}$$

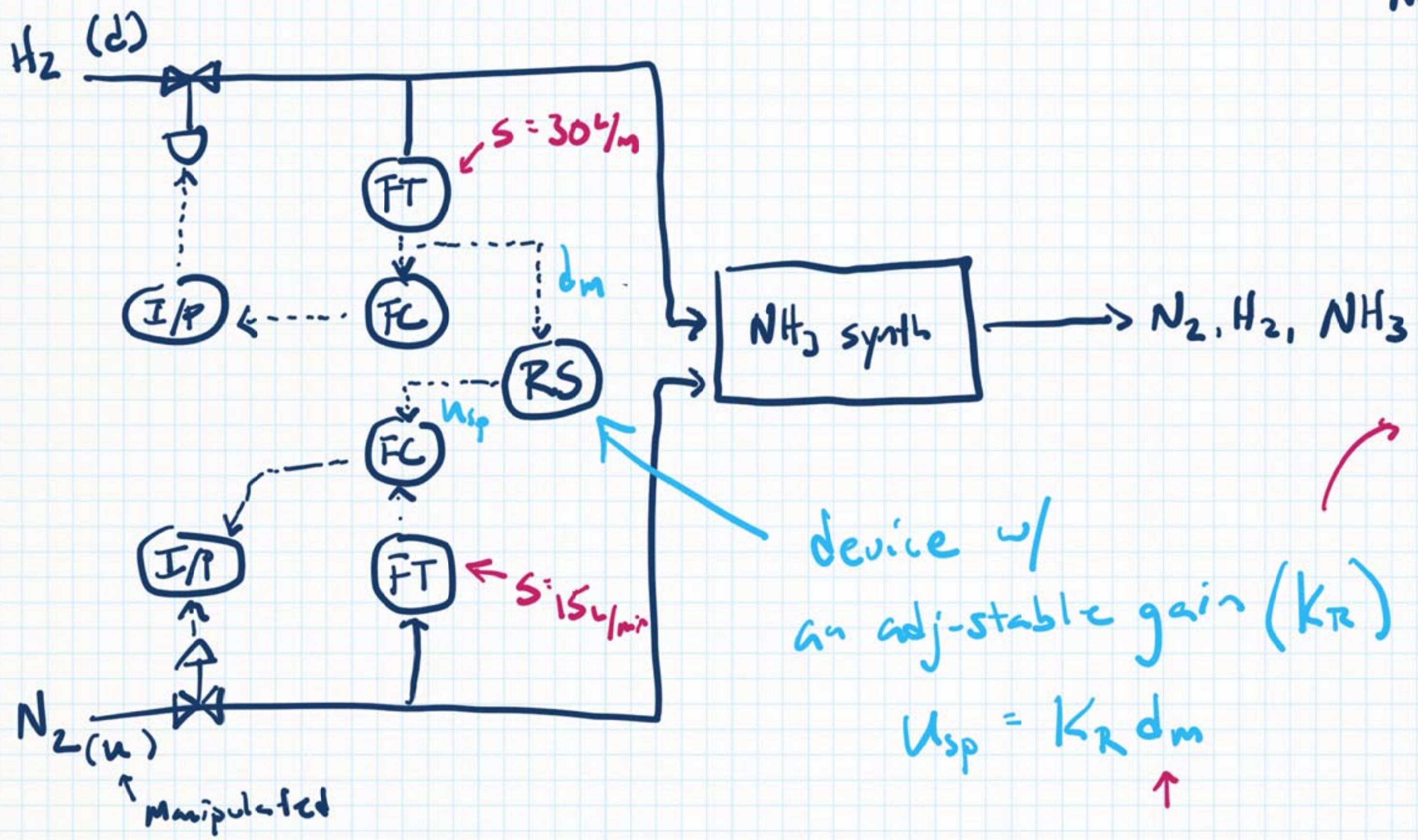
— spans of Flow transmitters for disturbance variable and measure

$\boxed{\text{Ex}}$ Stoichiometric Control for Ammonia Synthesis

$$3H_2 + N_2 = 2NH_3$$

$\frac{H_2}{N_2}$ ratio 3:1

$$R_d = \frac{u}{d} = \frac{1}{3}$$



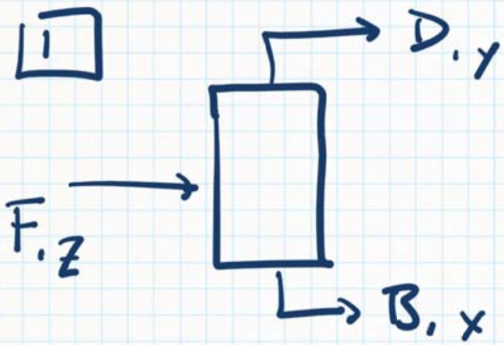
$$K_R = R_d \frac{S_d}{S_m}$$

$$K_R = \frac{1}{3}\left(\frac{30\ \text{L/min}}{15\ \text{L/min}}\right)$$

$$= 2/3$$

Designing FF systems : $\boxed{1}$ Steady State $\boxed{2}$ Dynamic

$\boxed{1}$



$$\bar{F} = \bar{D} + \bar{B}$$

$$\bar{F}\bar{z} = \bar{D}\bar{y} + \bar{B}\bar{x}$$

solve for B and then

$$\bar{D} = \frac{\bar{F}(\bar{z} - \bar{x})}{\bar{y} - \bar{x}}$$

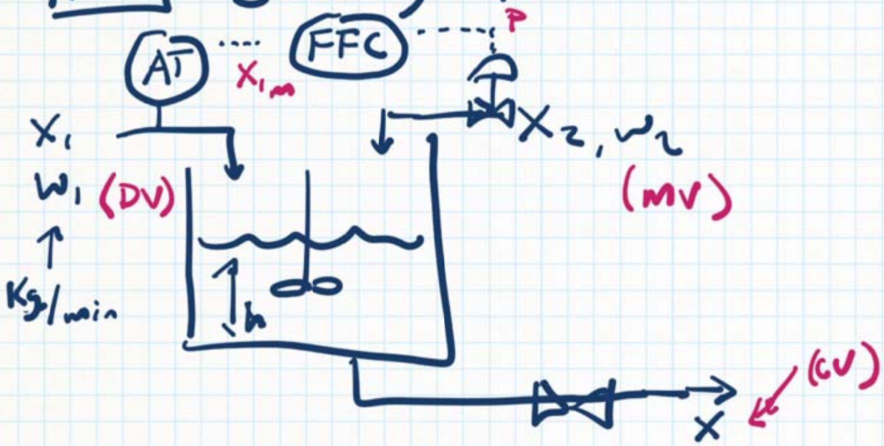
Hold these at sp

"FFC is continual attempt to balance the material or energy that must be delivered to process against a disturbance"

$$D(t) = \frac{F(t)\left[Z(t) - x_{sp}\right]}{\left[y_{sp} - x_{sp}\right]}$$

FF. control law for distillation column

$\boxed{\text{Ex 2}}$ Blending System



$$w = C_v\sqrt{h}$$

M.B. $\qquad \bar{w} = \bar{w}_1 + \bar{w}_2$

C.M.B. $\qquad \bar{x}\bar{w} = \bar{w}_1\bar{x}_1 + \bar{w}_2\bar{x}_2$

combine + solve w_2 (MV)

$\boxed{\text{MB}}$

$$\bar{w}_2 = \frac{\bar{w}_1(\bar{x} - \bar{x}_1)}{\bar{x}_2 - \bar{x}}$$

$\boxed{A}$ measure this, convert to x_{1m} (mA)

$\boxed{B}$ Change this to controller output signal

$\boxed{A}$ Composition Measure

$$K_t = \frac{\text{measured signal}}{\text{measured flowrate}}$$

$$K_t = \frac{20 - 4\,\text{mA}}{S_t}$$

S_t ← span of flowrates

$$= \frac{x_{1m} - 4_{mA}}{x_1(t) - (x_1)_0} \Rightarrow x_{1m}(t) = K_t\left[x_{1(t)} - x_{1_0}\right] + 4$$

$\boxed{B}$ Pressure Transducer and Control Value

$$mA \longrightarrow \boxed{K_{IP}} \xrightarrow{psi} \boxed{K_V} \xrightarrow{L/min}$$

$$K_{IP} K_V = \frac{\text{flow rate}}{\text{controller output}} = \frac{W_2(t) - W_{2(0)}}{P(t) - 4\,mA}$$

$$W_2(t) = K_V K_{IP} \left[P(t) - 4 \right] + (W_2)_0$$

mass balance

Combine mass balance Eqn $\boxed{MB}$ w/ $\boxed{A}$ and $\boxed{B}$

mA coming off sensor

$$P(t) = C_1 + C_2 \left[\frac{K_t X_{sp} - X_{1m}(t) + C_3}{\bar{X}_2 - X_{sp}} \right]$$

mA out of controller

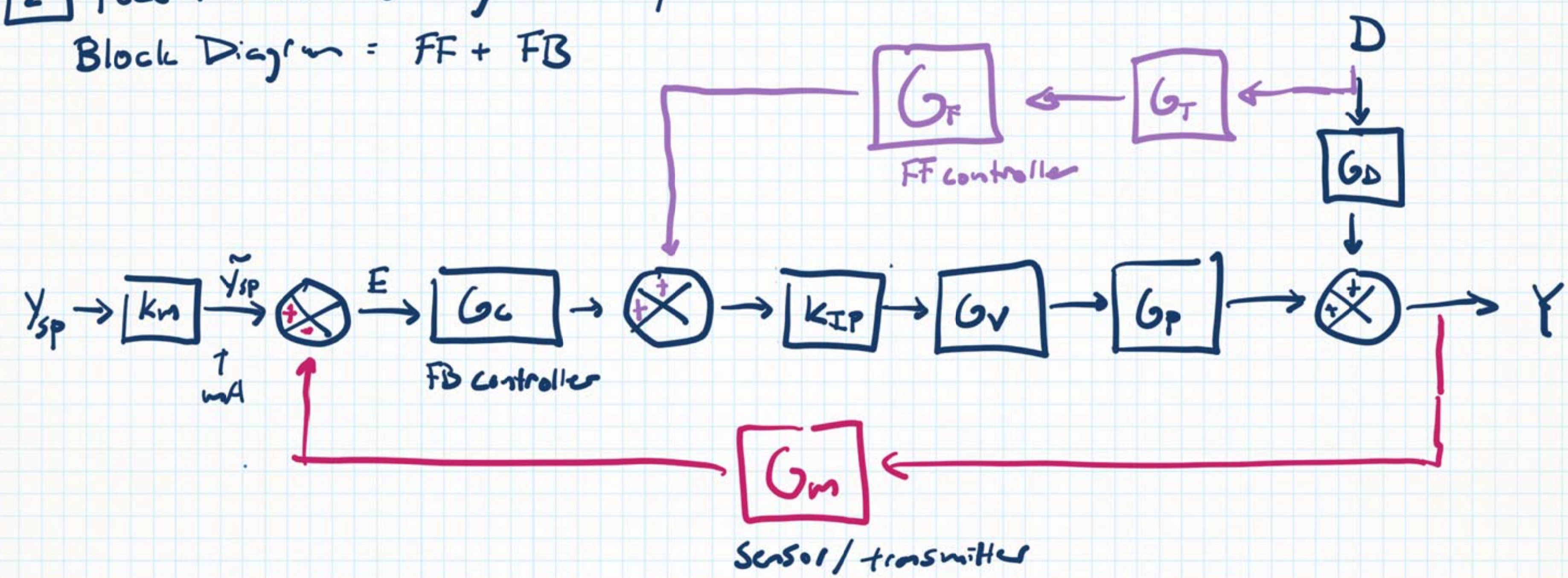
$$C_1 = \frac{4 - W_{2_0}}{K_V K_{IP}}$$

$$C_2 = \frac{\overline{W}}{K_V K_{IP} K_t}$$

$$C_3 = 4 + K_t (X_1)_0$$

$\boxed{2}$ Feed Forward Design = Dynamic Model

Block Diagram = FF + FB



$$\frac{Y(s)}{D(s)} = \frac{G_d + G_T G_f K_{IP} G_v G_p}{1 + G_c K_{IP} G_V G_P G_m}$$

Class 20: Feed Forward Control (w/ Dynamic Systems)

$$\frac{Y(s)}{D(s)} = \frac{G_d + G_t G_f G_v G_p}{1 + G_c G_v G_p G_m}$$

Perfect control $Y(s) = 0$

$$G_d + G_t G_f G_v G_p = 0$$

$$G_f = -\frac{G_d}{G_t G_v G_p}$$

Feed forward Controller TF.

$\boxed{\text{Ex 1}}$

$$G_t = K_t$$

$$G_v = K_v$$

$$G_d = \frac{K_d}{\tau_d s + 1}$$

$$G_p = \frac{K_p}{\tau_p s + 1}$$

$$G_f = -\frac{K_d}{(K_t K_v K_p)} \left(\frac{\tau_p \cdot s + 1}{\tau_d \cdot s + 1} \right)$$

Lead

Lag

"Lead-Lag TF"

$\boxed{\text{Ex 2}}$

$$G_d = \frac{K_d}{\tau_d \cdot s + 1} \qquad G_p = \frac{K_p e^{-\theta s}}{\tau_p \cdot s + 1}$$

NOT physically realizable

$$G_f = -\left(\frac{K_d}{K_t K_v K_p}\right)\left(\frac{\tau_p \cdot s + 1}{\tau_d \cdot s + 1}\right)e^{+\theta s}$$

handle this negative time delay by lumping θ w/ τ_p

$\tau_p + \theta$ = New lead time constant

$\boxed{\text{Ex 3}}$

$$G_d = \frac{K_d}{\tau_d \cdot s + 1} \qquad G_p = \frac{K_p}{(\tau_{p_1} \cdot s + 1)(\tau_{p_2} \cdot s + 1)}$$

$$G_f = -\left(\frac{K_d}{K_t K_v K_p}\right)\left(\frac{(\tau_{p_1} \cdot s + 1)(\tau_{p_2} \cdot s + 1)}{(\tau_d \cdot s + 1)}\right)$$

← Also NOT physically realizable

$\tau_{p_1} + \tau_{p_2}$ = New lead time constant

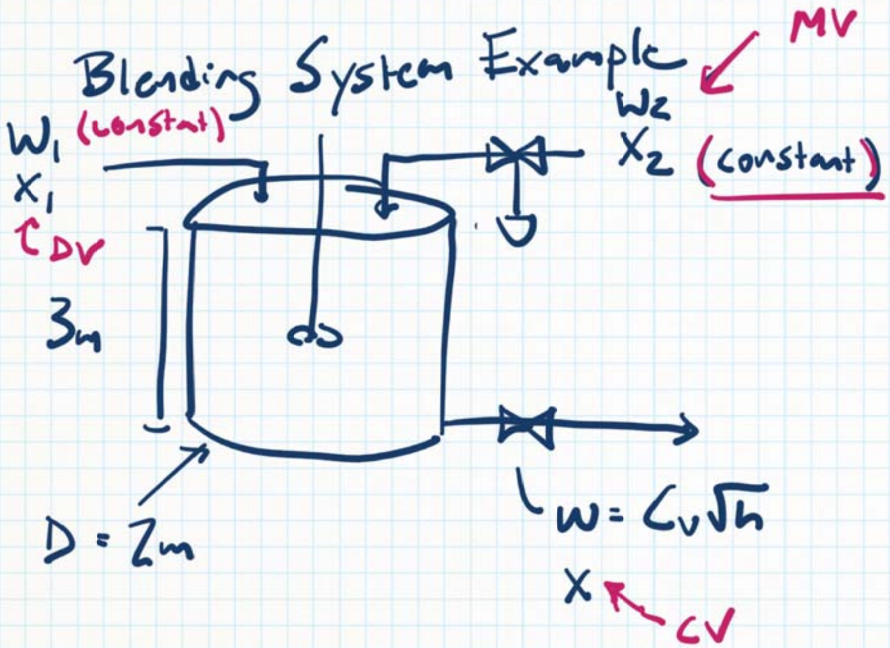
Stability = G_f does NOT appear in the characteristic eqn. for the way it is typically connected (where both controller (FB + FF) outputs are summed)

↳ Thus, it does NOT affect stability …

Typical Form of FFC

$$G_f(s) = \frac{U(s)}{D(s)} = \frac{K_f\,(\tau_1 s + 1)}{(\tau_2 s + 1)}\, e^{-\theta s}$$

Blending System Example



Nominal Steady State

$\bar{w}_1 = 650\ \frac{kg}{min}$ $\quad \bar{x}_1 = 0.2$

$\bar{h} = 1.5m$

$\bar{w}_2 = 350\ \frac{kg}{min}$ $\quad \bar{x}_2 = 0.6$

$\rho = 1g/cm^3$

$\bar{x} = 0.34$

Using derivation from class 19 we get the following

$$p(t) = 4 + 1.083\left[\frac{32x_{sp} - x_{1m}(t) + 4}{0.6 - x_{sp}}\right]$$

With DYNAMICS:

$$G_f = -\frac{G_d}{K_{IP} G_c G_v G_p}$$

$$G_{p(s)} = \frac{K_p}{\tau s + 1} \qquad G_{d(s)} = \frac{K_d}{\tau s + 1}$$

$$\tau = \frac{V_p}{\overline{w}} \quad \leftarrow \pi R^2 h$$

Chp. 4 (derived Tank problem
where we have K_p & K_d)

$$\left.\begin{aligned} K_p &= \frac{\overline{x_2} - \overline{x}}{\overline{w}} \qquad K_d = \frac{\overline{w_1}}{\overline{w}} \end{aligned}\right\}$$

$$G_f = \frac{-G_d}{K_{IP} G_t G_v G_p}$$

$$= \frac{-\dfrac{0.65}{\cancel{4.7}1s+1}}{(0.75)(32e^{-s})\left(\dfrac{25}{0.0833 \cdot s+1}\right)\left(\dfrac{2.6 \times 10^{-4}}{(\cancel{4.7}1s+1)}\right)}$$

Assume PI feedback controller

$K_c = 21.9$

$\tau_I = 3.33$ min

$$G_c = K_c\left(1 + \frac{1}{\tau_I \cdot s}\right)$$

$$G_f = -4.17(0.0833 \cdot s + 1)e^{+s}$$

$$= \frac{-4.17(1.0833 \cdot s + 1)}{\alpha(1.0833) \cdot s + 1}$$

where $\alpha = .1$

$\boxed{1}$ disregard our negative time delay

$\boxed{2}$ Add θ to lead time constant

$\boxed{3}$ Make a lag time constant that is 10% of our new lead constant

Use 'impulse' function in Matlab to model response

FF by itself is not good. Include 'Feedback Trim'

- modeling errors
- unmeasured disturbances

Tuning (process after you have best guess values for G_f)

$$G_f = \frac{K_f(\tau_1 \cdot s + 1)e^{-\theta s}}{(\tau_2 \cdot s + 1)}$$

Step 1 set τ_1 and τ_2 to zero to check gain

→ increase disturbance variable 3-5%

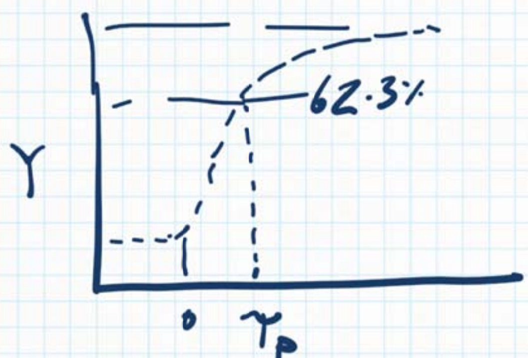
→ Goal: minimize offset

Step 2 τ_1 and τ_2 use process data for first guess (fit of exp. data)

$\tau_1 : \tau_p$ (lead)

$\tau_2 : \tau_D$ (lag)

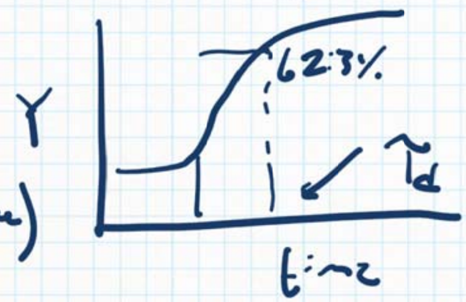
Servo step



— Seen this before (open loop step test)

$$K_p = \frac{Y_\infty - Y_0}{\Delta u} \leftarrow \text{magnitude set point step}$$

disturbance step (set point const, step disturbance)



$$K_d = \frac{Y_\infty - Y_0}{\Delta d} \leftarrow \text{magnitude of disturbance step}$$

No Data? SAD ....

$$\frac{\tau_1}{\tau_2} = 2 \qquad \frac{\tau_1}{\tau_2} = 0.5$$

$\boxed{\text{Step 3}}$ Fine tuning τ_1 and τ_2

Class 22 (The FINAL Lecture) Cascade Control,
(and some other Advanced Techniques)

Enhanced Disturbance Rejection

(1) ▫ Feed Forward Control w/ FB Trim

(+) directly measures disturbance

(−) Accurate model is needed, additional sensor

(·) controls for ONE SPECIFIC disturbance

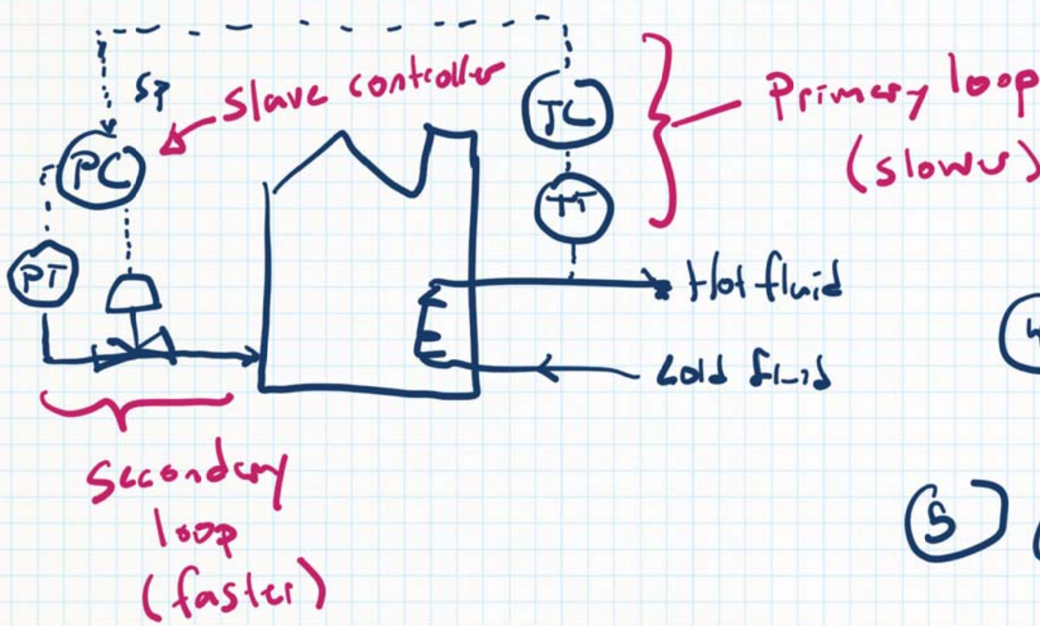
(2) Cascade Control

- 2 sensors, 2 controllers, 1 final control element
- 2 nested feedback loops
- identify secondary disturbance variable that can be controlled quickly
- Try this first, if it fails go to FFC w/ FB

Objective: Disturbance Rejection

Works well if disturbance is in the hot fluid stream

What if we have disturbance here?



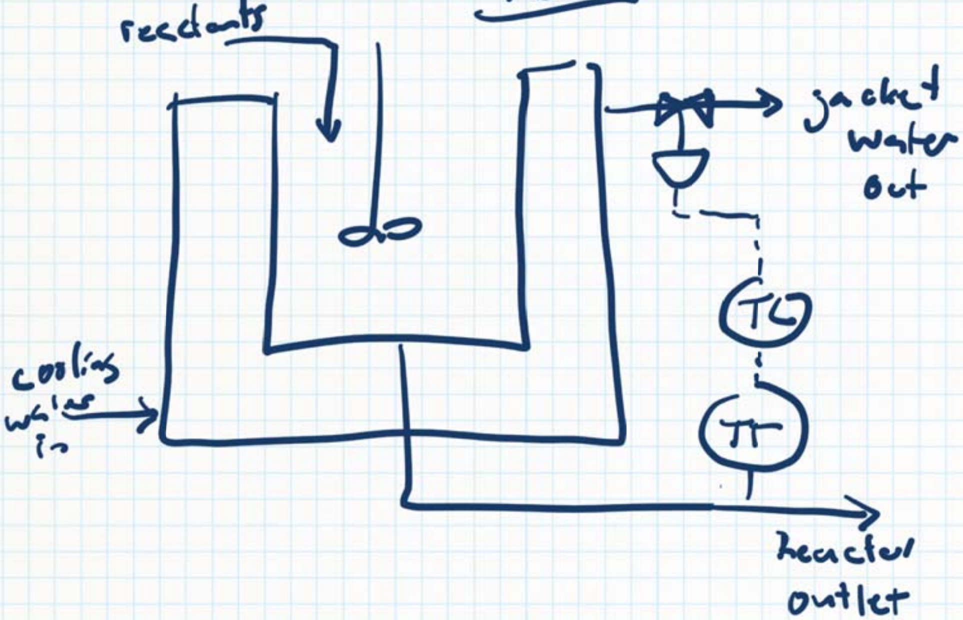
Findings

1. 2nd variable must be measurable
2. final control element must have an effect on 1st + 2nd variable
3. 2nd variable must be 'inside' the first variable
4. Settling time for the inner loop (2nd) must be significantly faster than outer
5. Output from Master controller is S.P. for the slave...

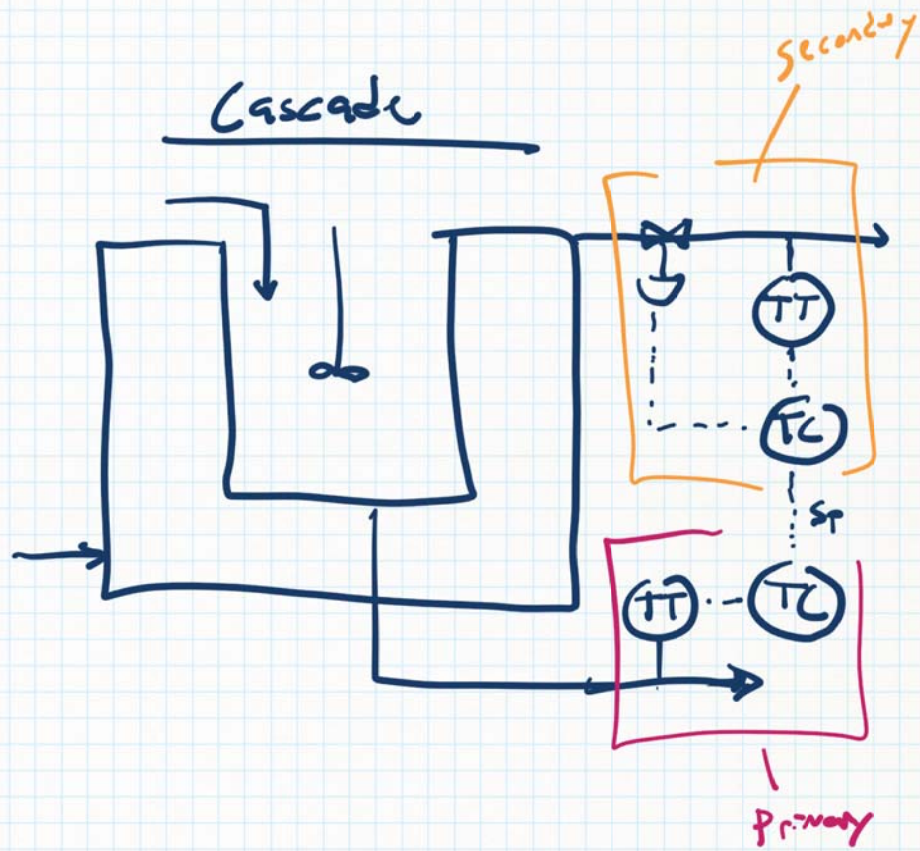
Ex2. Cascade control

Reactor w/ heated jacket

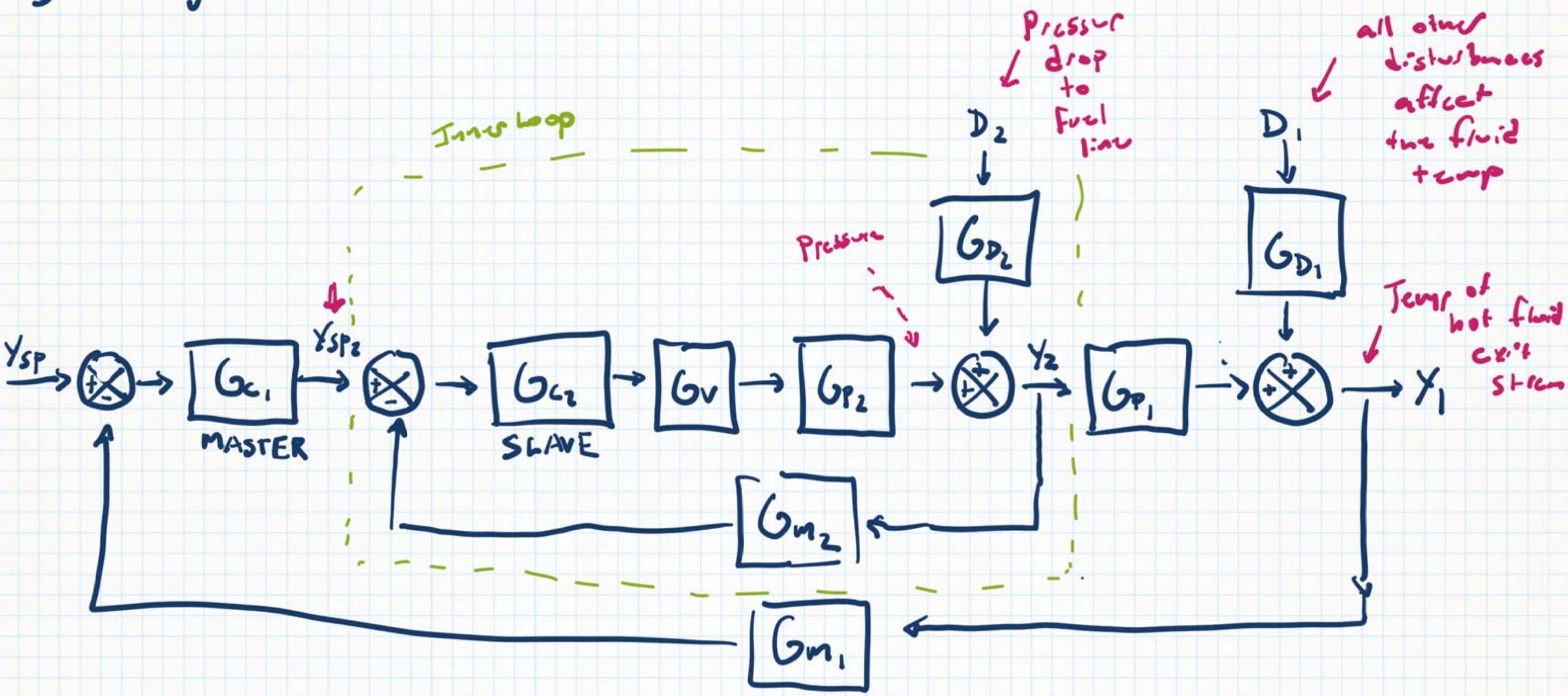
FB



Cascade



Block Diagram Cascade Control (units from Furnace Ex.)



Transfer functions for Cascade Block diagram

Inner Loop: disturbance

$$\frac{Y_1}{D_2} = \frac{G_{P_1} G_{D_2}}{1 + G_{P_2} G_V G_{C_2} G_{m_2} + G_{P_1} G_{P_2} G_V G_{C_2} G_{C_1} G_{m_1}}$$

set point

$$\frac{Y_2}{Y_{sp_2}} = \frac{G_{C_2} G_V G_{P_2}}{1 + G_{C_2} G_V G_{P_2} G_{m_2}}$$

Outer Loop whole System

disturbance

$$\frac{Y_1}{D_1} = \frac{G_{D_1} (1 + G_{C_2} G_V G_{P_2} G_{m_2})}{1 + G_{C_2} G_V G_{P_2} G_{m_2} + G_{C_1} G_{C_2} G_V G_{P_2} G_{P_1} G_{m_1}} \leftarrow$$

Set point

$$\frac{Y_1}{Y_{sp_1}} = \frac{G_{C_1} G_{C_2} G_V G_{P_1} G_{P_2}}{1 + G_{C_2} G_V G_{P_2} G_{m_2} + G_{C_1} G_{C_2} G_V G_{P_1} G_{P_2} G_{m_1}} \leftarrow$$

Example Problem

$G_v = \frac{5}{s+1}$ $\quad G_{P_1} = \frac{4}{(4s+1)(2s+1)}$ $\quad G_{P_2} = 1$

$K_{c_2} = 4$ $\quad G_{D_2} = 1$ $\quad G_{m_1} = 0.05$ $\quad G_{m_2} = 0.2$

$G_{D_1} = \frac{1}{3s+1}$

Settling time of inner loop (Time constant)

$$\frac{Y_2}{Y_{sp2}} = \frac{G_{c2} G_v G_{p2}}{1 + G_{c2} G_v G_{p2} G_{m2}} = \frac{(4)(5/s+1)}{(1+4(5/(s+1))(0.2)} = \frac{4}{0.2s+1}$$

with cascade

τ

compare to F.B. $G_{c_2} = 1$, $G_{M_2} = 0$

$$\frac{Y_2}{Y_{sp2}} = \frac{1 \cdot G_v G_{p2}}{1+0} = \frac{5}{s+1}$$

$\tau = 1$

5x faster with cascade

$K_{c_1} \leftarrow$ P only controller, (How much higher (aggressive) can we make this gain w/ cascade vs. FB)

$$1 + G_{c_2} G_v G_{p_2} G_{m_2} + G_{c_1} G_{c_2} G_v G_{p_2} G_{p_1} G_{m_1} = 0$$

$$1 + 4\left(\frac{s}{s+1}\right)(0.2) + K_{c_1}(4)\left(\frac{s}{s+1}\right)\left(\frac{4}{(4s+1)(2s+1)}\right)(0.05) = 0$$

$$1 + \frac{4}{(s+1)} + \frac{4K_{c_1}}{(s+1)(4s+1)(2s+1)} = 0$$

$$1386 - 32K_{c_1} > 0$$

$$K_{c_1} < 43.3$$

$$(s+1)(4s+1)(2s+1) + 4(4s+1)(2s+1) + 4K_{c_1} = 0$$

Routh

$$8s^3 + 14s^2 + 7s + 1 + 32s^2 + 24s + 4 + 4K_{c_1} = 0$$

$$8s^3 + 46s^2 + 31s + \underbrace{(5 + 4K_{c_1})} = 0$$

$$\begin{array}{l|ll} \text{odd} & 8 & 31 \\ \text{even} & 46 & 5 + 4K_{c_1} \\ \rightarrow & \frac{1386 - 32K_{c_1}}{46} & \end{array}$$

(+)

$$5 + 4K_{c_1} > 0$$

$$K_{c_1} > -5/4$$

Same problem FB only

$$1 + G_{c_1} G_v G_{P_1} G_{P_2} G_{M_1} = 0$$

$$1 + K_{c_1}\left(\frac{s}{s+1}\right)\left(\frac{4}{(4s+1)(2s+1)}\right)(0.05) = 0$$

$$(s+1)(4s+1)(2s+1) + K_{c_1} = 0$$

$$8s^3 + 14s^2 + 7s + (K_{c_1}+1) = 0$$

$$\rightarrow K_{c_1} > -1$$

Tuning:
See book

Routh Array

8	7
14	$K_{c_1}+1$
$\frac{90-8K_{c1}}{14}$	

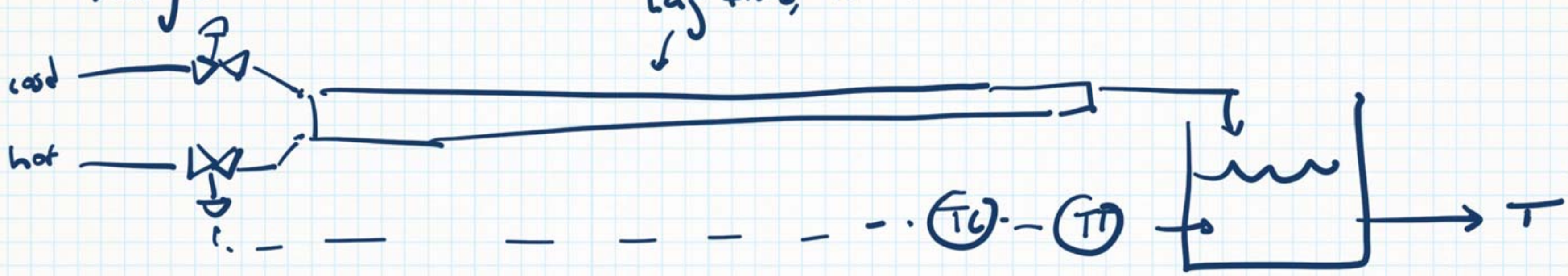
$\rightarrow$ positive

$$90 - 8K_{c_1} > 0$$

$$K_{c_1} < 11.25$$

w/ Cascade we can be 4x as aggressive

Large Dead Time



if $\theta \gg \tau$, sensor does not 'see' controller action

if $T < T_{sp}$, valve open, but T doesn't respond for a long time

Smith Predictor (1957)

Process model → $\tilde{G}^*(s) = G^*(s)$ No time delay component
→ $e^{-\theta s}$

⚠ - only works well if you have a ROBUST model

$$\frac{Y}{Y_{sp}} = \frac{G_c G^* \exp(-\theta s)}{1 + G_c G^*}$$

eliminates delay in C.E.

Model Predictive Control (MPC)
Chp. 20

Few other "Advanced" control Methods in Chp. 16

- Inferential Control - cannot measure your desired CV.

  Model ⇒ "soft sensor"

  take many measurements, use model to predict value of interest

- Selective control / override systems
  - high selector
  - (Low)
  - Median selector
  - Split range
  - Override

- Non-linear
  - do not have a constant controller gain
  - (K_c will change)
  - → Gain Scheduling - controller gains for different error ranges
  - → Fuzzy Logic → "old times controller"

- Adaptive control → all control parameters (K_c, τ_I, τ_D) are adjusted automatically to compensate for changing process or environmental conditions

→ Ambient environment (Seasonal, daily)

example: Creepy NEST thermostat

↳ Advanced Topics

Digital control - chp. 17

Multivariable control → chp 18 ✓

→ Model predictive control → chp. 19