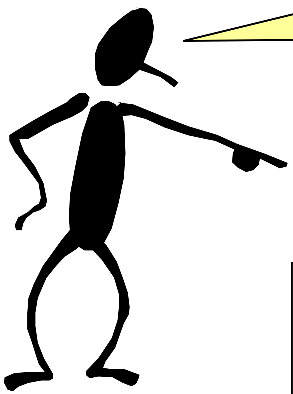
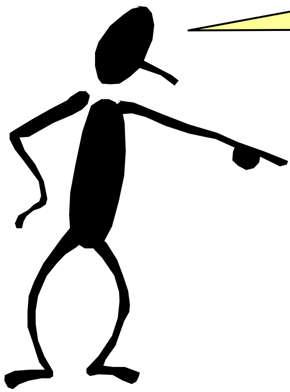
CHAPTER 13: FEEDBACK PERFORMANCE



When I complete this chapter, I want to be able to do the following.

- **Apply two methods for evaluating control performance: simulation and frequency response**
- **Apply general guidelines for the effect of**
  - feedback dead time
  - disturbance time constant
  - MV variability
  - sensor and final element dynamics

CHAPTER 13: FEEDBACK PERFORMANCE



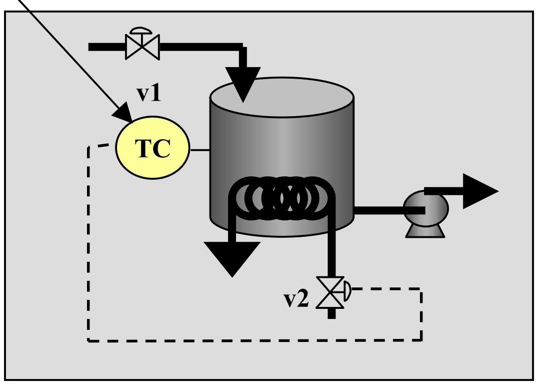
Outline of the lesson.

- **Apply dynamic simulation**
- **Apply frequency response to closed-loop performance**
- **Guidelines for the effects of the process**
- **Guidelines for the effects of the control system**

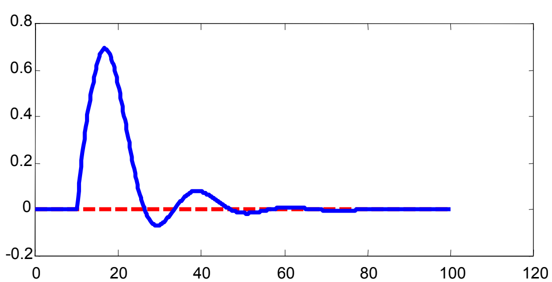
CHAPTER 13: FEEDBACK PERFORMANCE

How do we achieve the performance that we want?

$$MV(t) = K_c\left[E(t) + \frac{1}{T_I}\int_0^t E(t')dt' - T_d\frac{d\,CV}{dt}\right] + I$$



- **Select controlled variable**
- **Select manipulated variable**
- **Design process equipment**
- **Instrumentation**
- **PID modes and tuning**



- **Is this acceptable?**
- **Is this the best we can achieve?**

CHAPTER 13: FEEDBACK PERFORMANCE

Evaluating control performance

- **During design, test possible plant changes, and develop principles for guidelines**

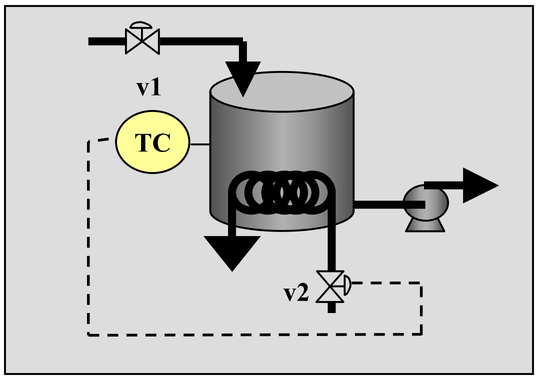
  - Dynamic simulation
  - Frequency Response

- **During plant operation**

  - Fine tuning guidelines for set point
  - Complementary guideline for step disturbance
  - Monitor the performance

CHAPTER 13: FEEDBACK PERFORMANCE

Dynamic simulation solves the equations describing the process and controller - numerically because of complexity of systems. For example,



$$V\frac{dC_A}{dt} = F(C_{A0} - C_A) - Vk_0 e^{-E/RT} C_A$$

$$V\rho C_P \frac{dT}{dt} = F\rho C_p (T_0 - T) - (\Delta H_{rxn}) V k_0 e^{-E/RT} C_A$$
$$- UA(T - (T_{cin} + T_{cout}))$$

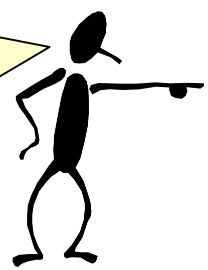
$$U \approx h_{in} = aF_c^{\,0.6} = (v) C_{v\,\mathbf{max}} \sqrt{\frac{\Delta P}{\rho_c}}$$

$$\tau_{sensor} \frac{dT_m}{dt} = (T_m - T)$$

$$\tau_{valve} \frac{dv}{dt} = (v - MV)$$

$$MV = K_c \left[(T_{SP} - T_m) + \frac{1}{T_I} \int_0^t (T_{SP} - T_m) dt' \right]$$

Many numerical methods; Euler, Runge-Kutta, and other.



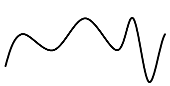
CHAPTER 13: FEEDBACK PERFORMANCE

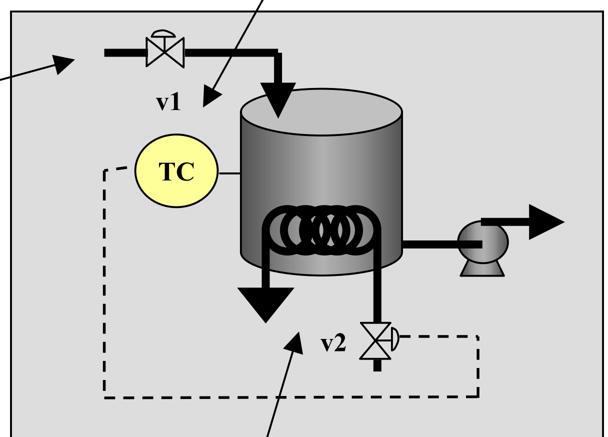
Dynamic simulation is general and powerful.

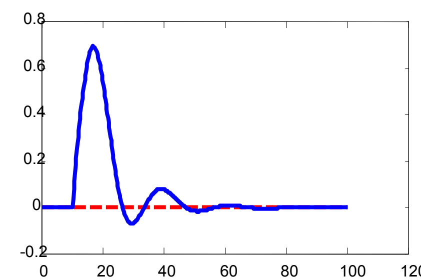
Detail for controller and sensors, e.g., valve saturation and sensor non-linearity

All process variables can be predicted, including those not measured

Process disturbances can be essentially any function,

- **step**
- **sine**
- 



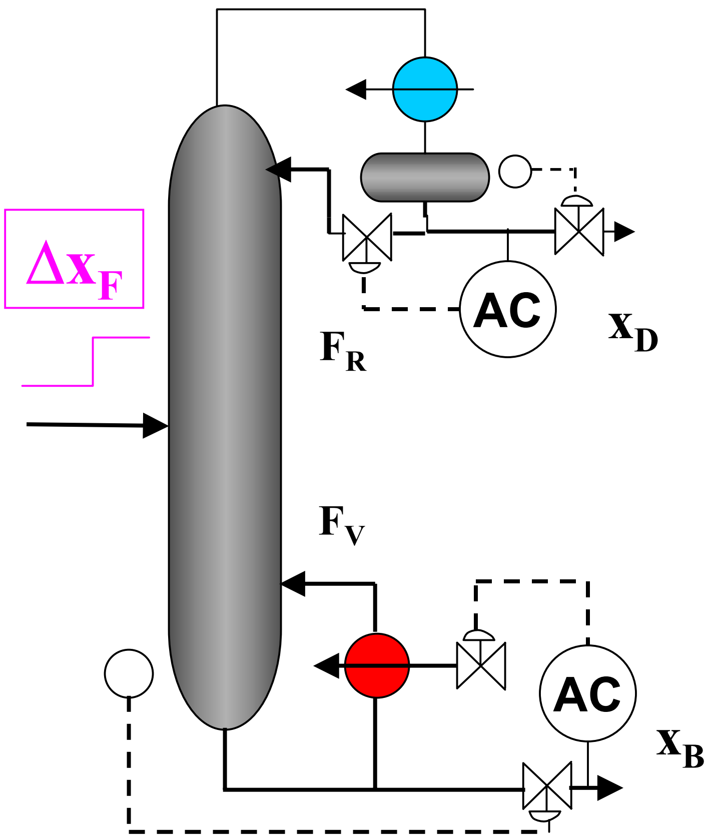


Process models can be linearized or detailed non-linear

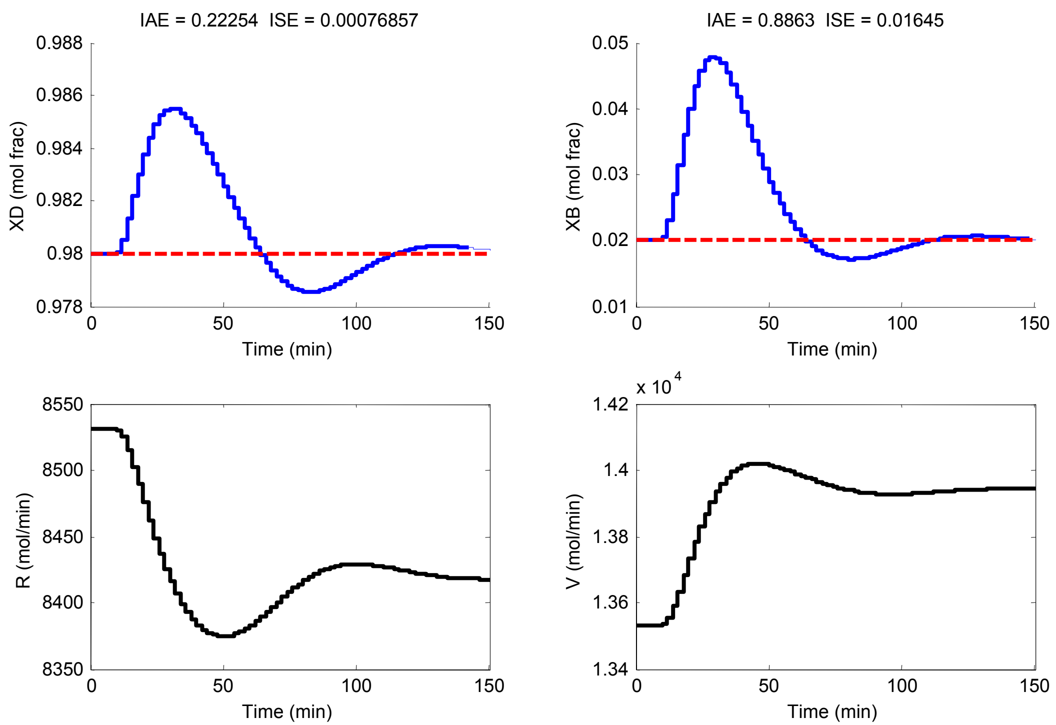
Results are easily interpreted, entire transient available

CHAPTER 13: FEEDBACK PERFORMANCE

Dynamic simulation is general and powerful.



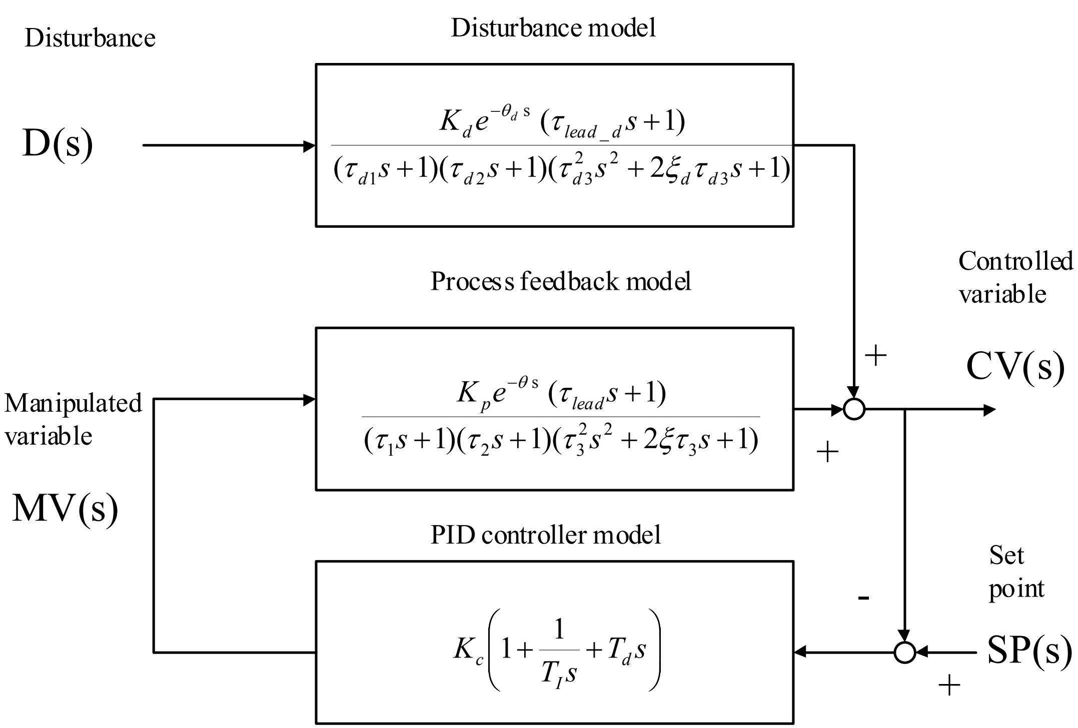
DISTIL: Results of detailed, non-linear, tray-by-tray dynamic model with PID feedback controllers. Simulation in MATLAB.

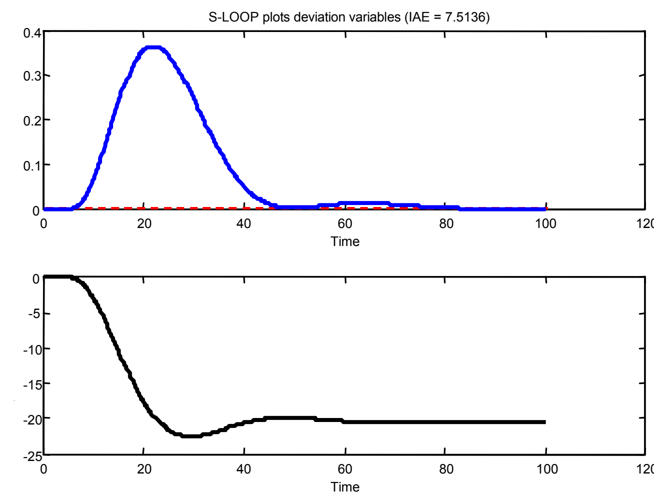


CHAPTER 13: FEEDBACK PERFORMANCE

Dynamic simulation is general and powerful.

Simulation of single-loop linear systems is easily achieved using the S_LOOP program in MATLAB. Cases are possible for systems with and without control for step inputs






```
                                        PRESENT VALUES
1) Total simulation time                 100.00
2) Time step for simulation              0.200

3) Set point change                      0.00
4) Disturbance change                    0.80
5) Process reaction curve MV input       0.00

6) Select continuous/digital controller, currently continuous
   (Controller executed every simulation time step)

7) Execute dynamic simulation
8) Return to main menu
```

CHAPTER 13: FEEDBACK PERFORMANCE

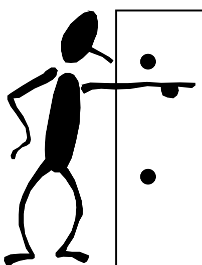
Frequency Response: determines the response of systems variables to a sine input.

Why do we study frequency response?

- Professors want to ruin the semester for students
- Perfect sine disturbances occur frequently in plants
- We want another case for dynamic simulation
- We use sine to characterize time-varying inputs, especially disturbances
- We can learn useful generalizations about control performance

CHAPTER 13: FEEDBACK PERFORMANCE

F… y Response: determines the response of systems … to a sine input.



Why do we study frequency response?

- Professors want to ruin the semester for students — No!
- Perfect sine disturbances occur frequently in plants — No!
- We want another case for dynamic simulation — No!
- We use sine to characterize time-varying inputs, especially disturbances — Yes!
- We can learn useful generalizations about control performance — Yes!

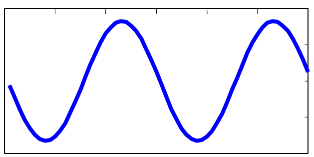
CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out without control

Three cases with amplitude 1 K and different T_{in} sine periods, P.

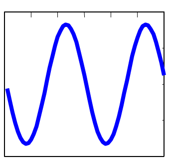
P = 5000 min

A 1



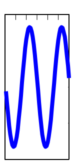
P = 50 min

B 1



P = 0.05 min

C 1

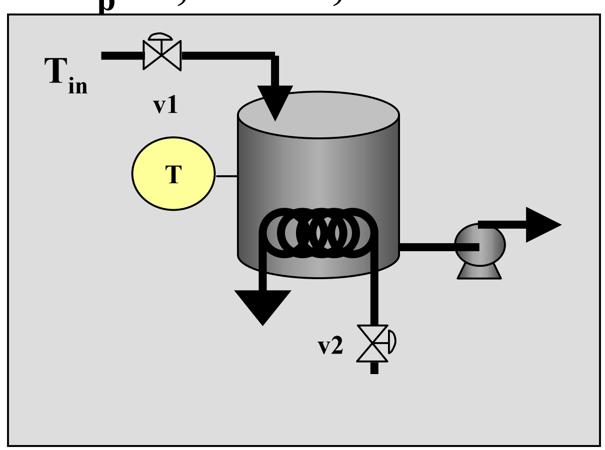


Process dynamics for disturbance T_{in} to T

$K_d = 1.5; \theta = 0 ; \tau = 5$ min

Process dynamics for MV v_2 to T

$K_p=1; \theta = 5 ; \tau = 5$ min



For each case, what is the output amplitude?

Let's do a thought experiment, without calculating!

CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out without control

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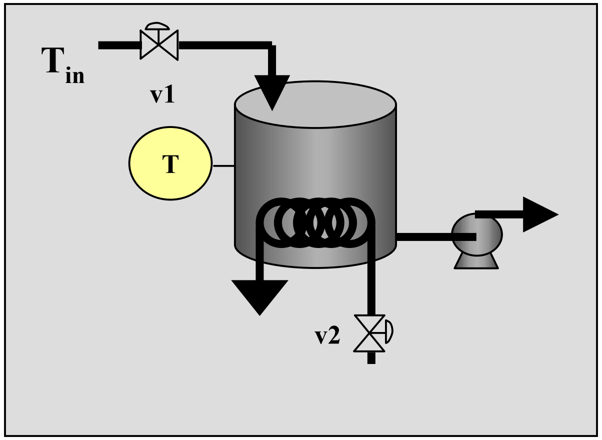
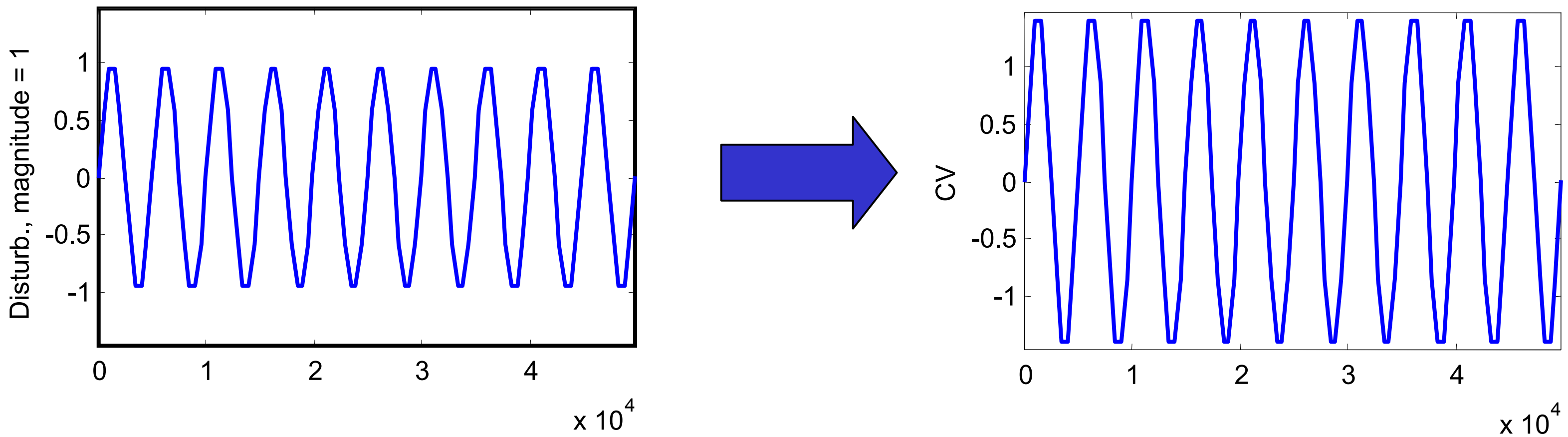


A   P = 5000 min

FREQUENCY =0.0012629 rad/time & AMP RATIO =1.4678



CHAPTER 13: FEEDBACK PERFORMANCE

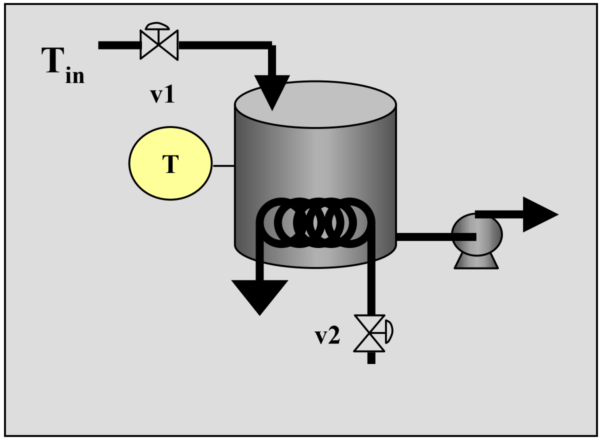
Frequency Response : Sine in $\Rightarrow$ sine out without control

Process dynamics for disturbance T_{in} to T

$K_d = 1.5;\ \theta = 0\ ;\ \tau = 5$ min

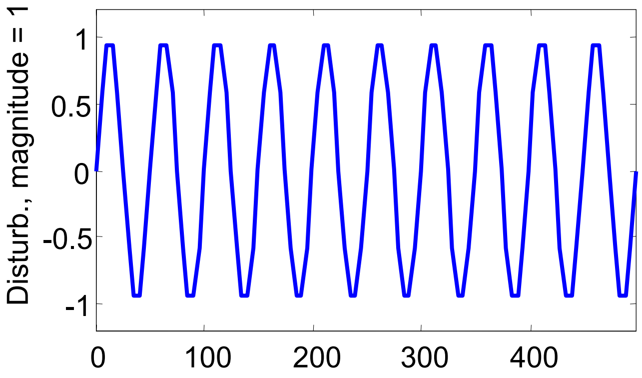
Process dynamics for MV v_2 to T

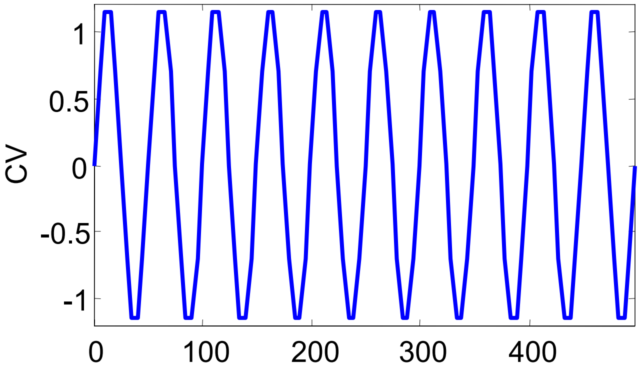
$K_p = 1\ ;\ \theta = 5$ min $;\ \tau = 5$ min



B **P = 50 min**

FREQUENCY =0.12629 rad/time & AMP RATIO =1.2115





CHAPTER 13: FEEDBACK PERFORMANCE

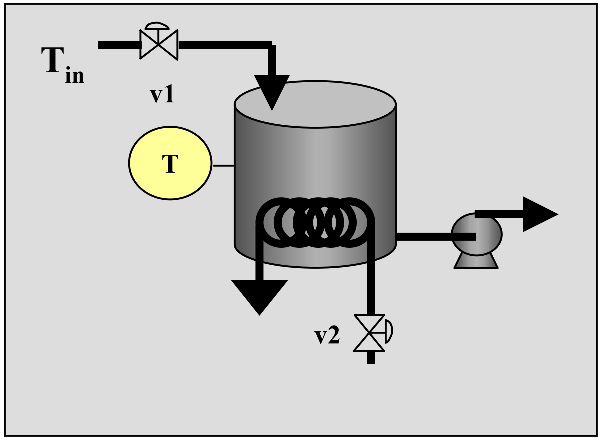
Frequency Response : Sine in $\Rightarrow$ sine out without control

Process dynamics for disturbance T_{in} to T

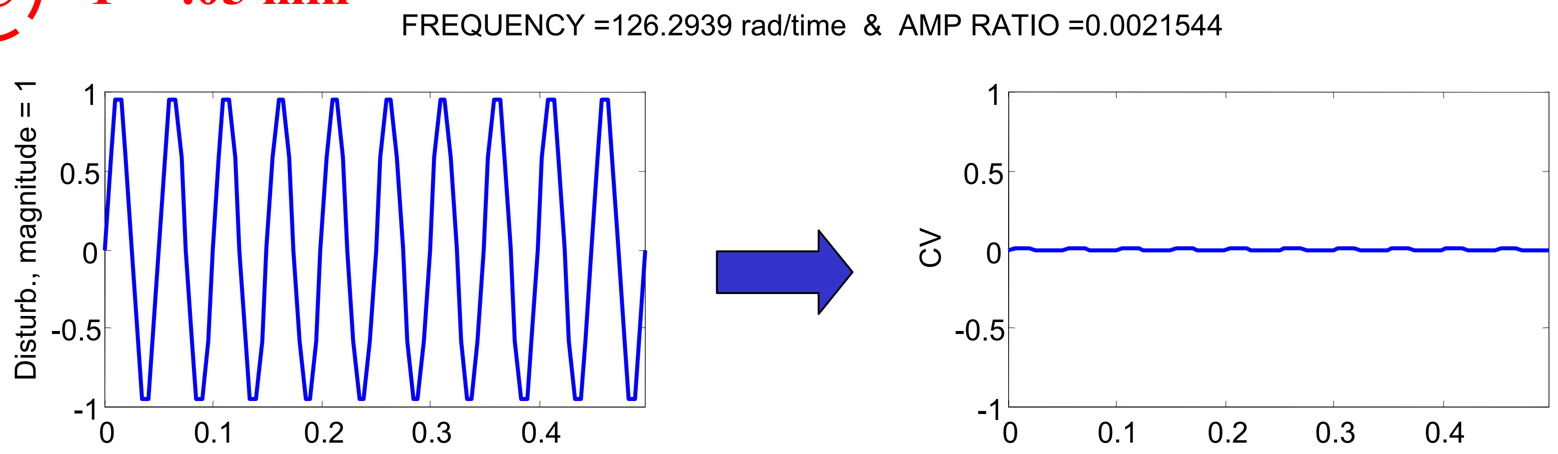
$K_d = 1.5; \theta = 0 ; \tau = 5$ min

Process dynamics for MV v_2 to T

$K_p = 1 ; \theta = 5$ min $; \tau = 5$ min



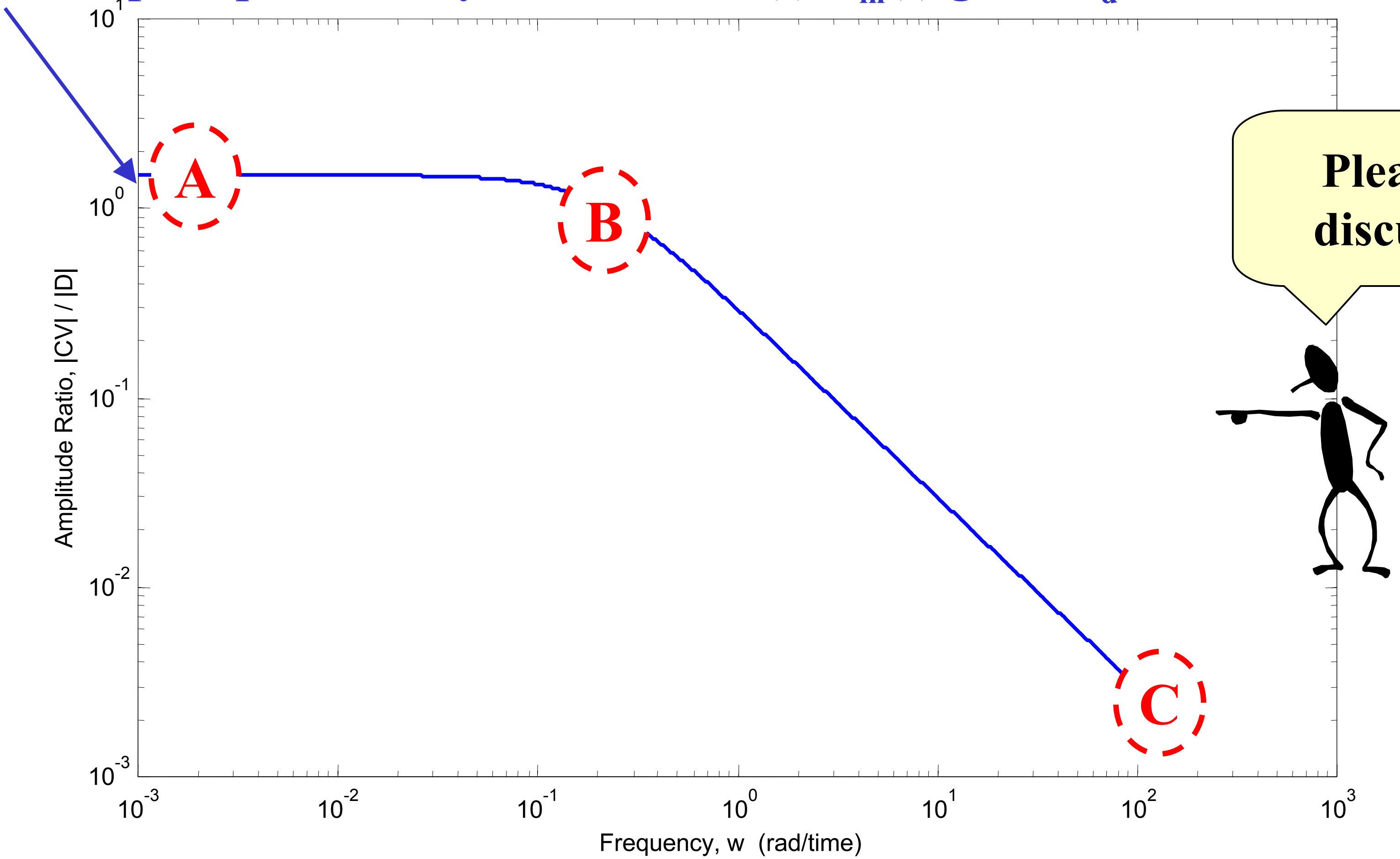
C P = .05 min



Frequency Response : Sine in $\Rightarrow$ sine out without control

Summarize the results for many frequencies in a Bode Plot

Intercept = quasi-steady-state is the $T(s)/T_{in}(s)$ gain, K_d = 1.5 K/K



CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out with control

Three cases with amplitude 1 K and different T_{in} sine periods, P.

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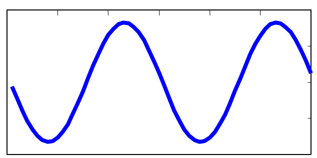
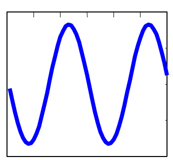
A 1



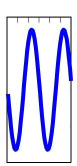
P = 50 min

B 1



P = 0.05 min

C 1



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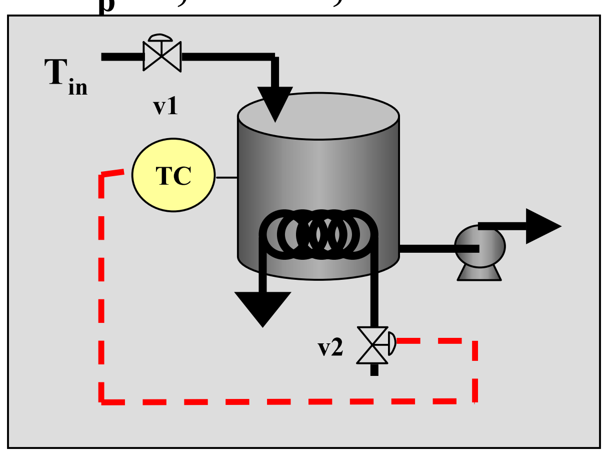
Process dynamics for MV v_2 to T

$K_p=1$; $\theta = 5$; $\tau = 5$ min



For each case, what is the output amplitude?

Let's do a thought experiment, without calculating!

CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out with control

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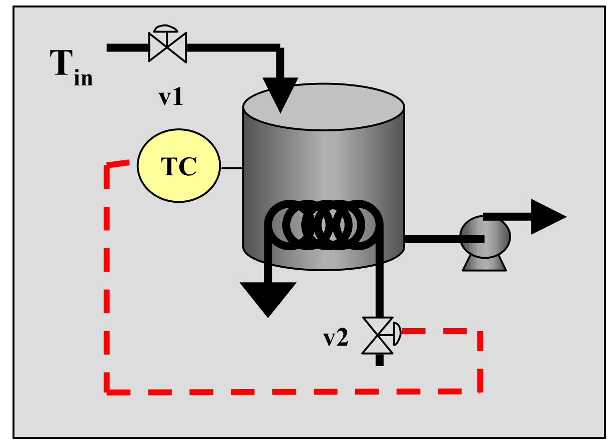
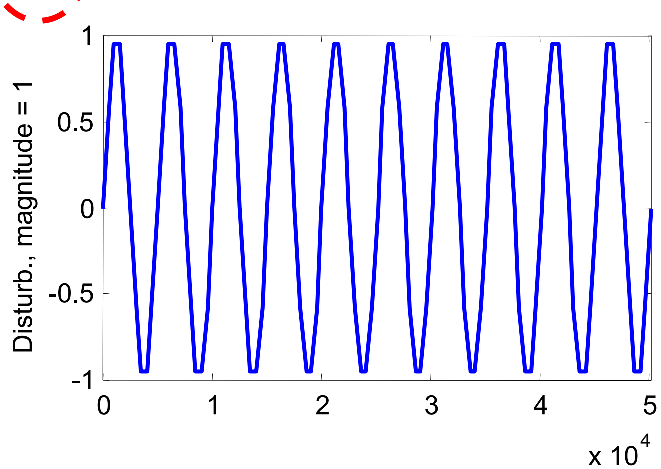
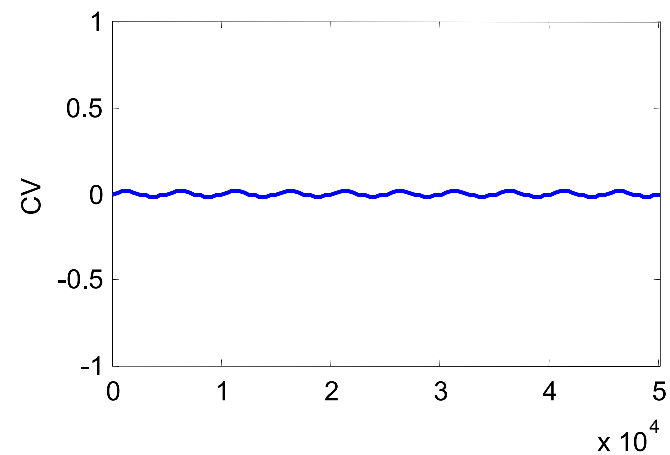


A P = 5000 min

FREQUENCY =0.0012496 rad/time & AMP RATIO =0.016156





CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out with control

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$K_d = 1.5;\ \theta = 0$ min ; $\tau = 5$ min

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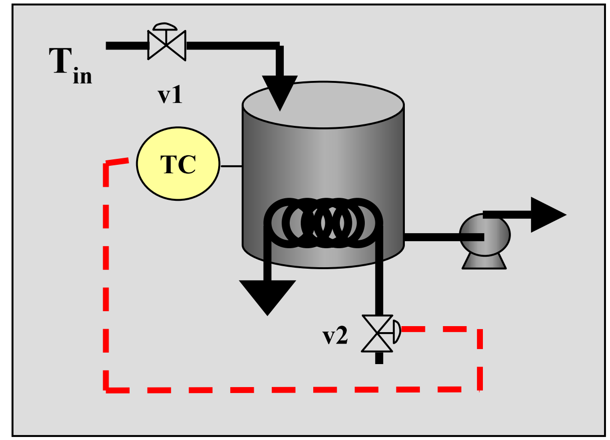
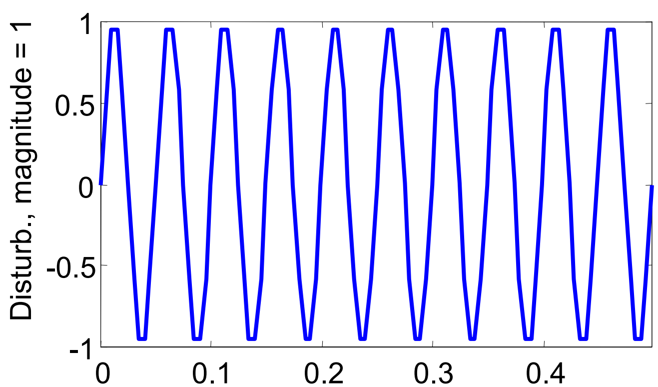
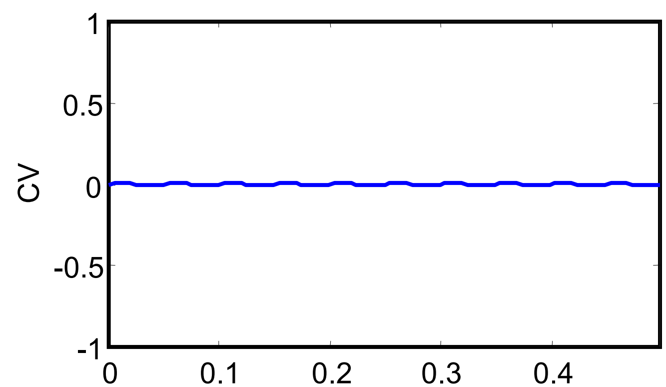
$K_p = 1;\ \theta = 5$; $\tau = 5$ min



C P = 0.050 min

FREQUENCY =126.2939 rad/time & AMP RATIO =0.0021544





CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out with control

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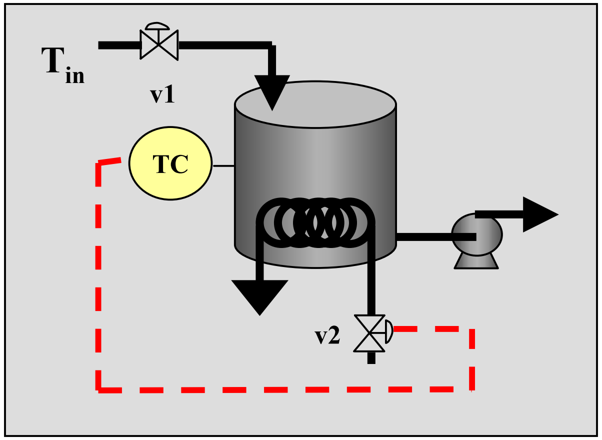
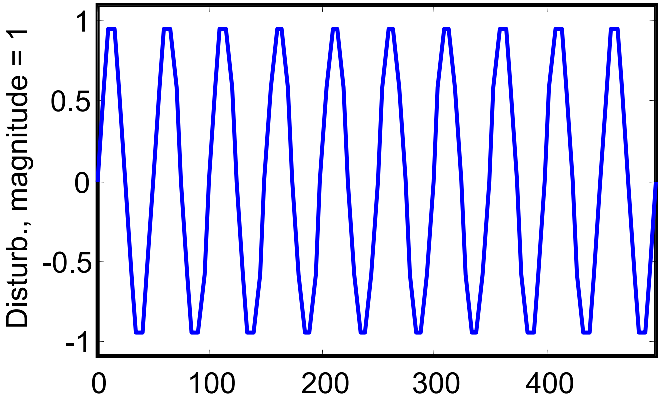
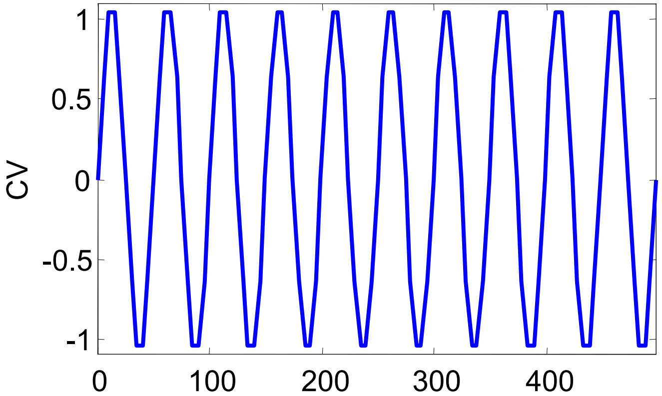


B P = 50 min

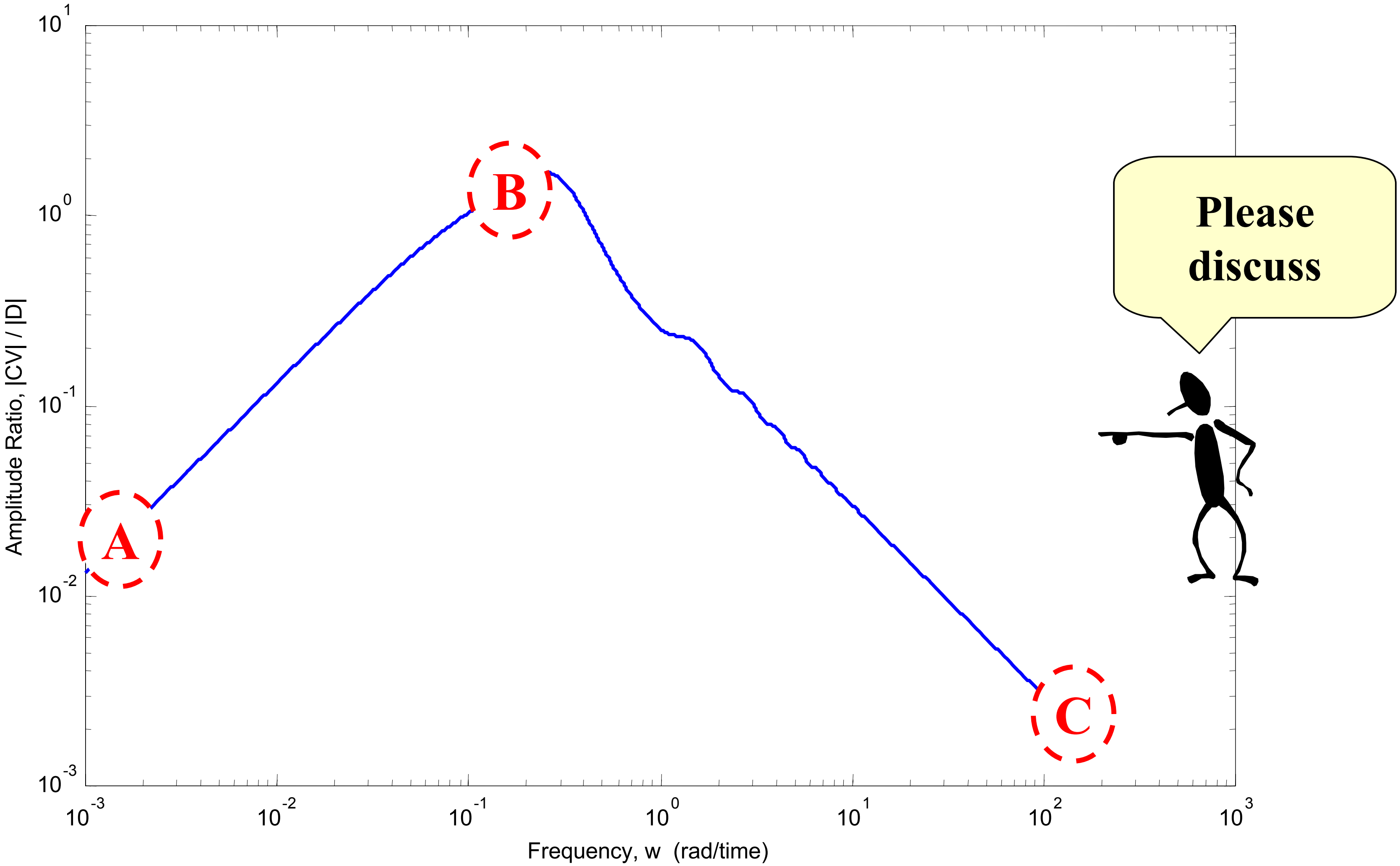
FREQUENCY =0.12629 rad/time & AMP RATIO =1.1007





Frequency Response : Sine in $\Rightarrow$ sine out with control

Summarize the results for many frequencies in a Bode Plot



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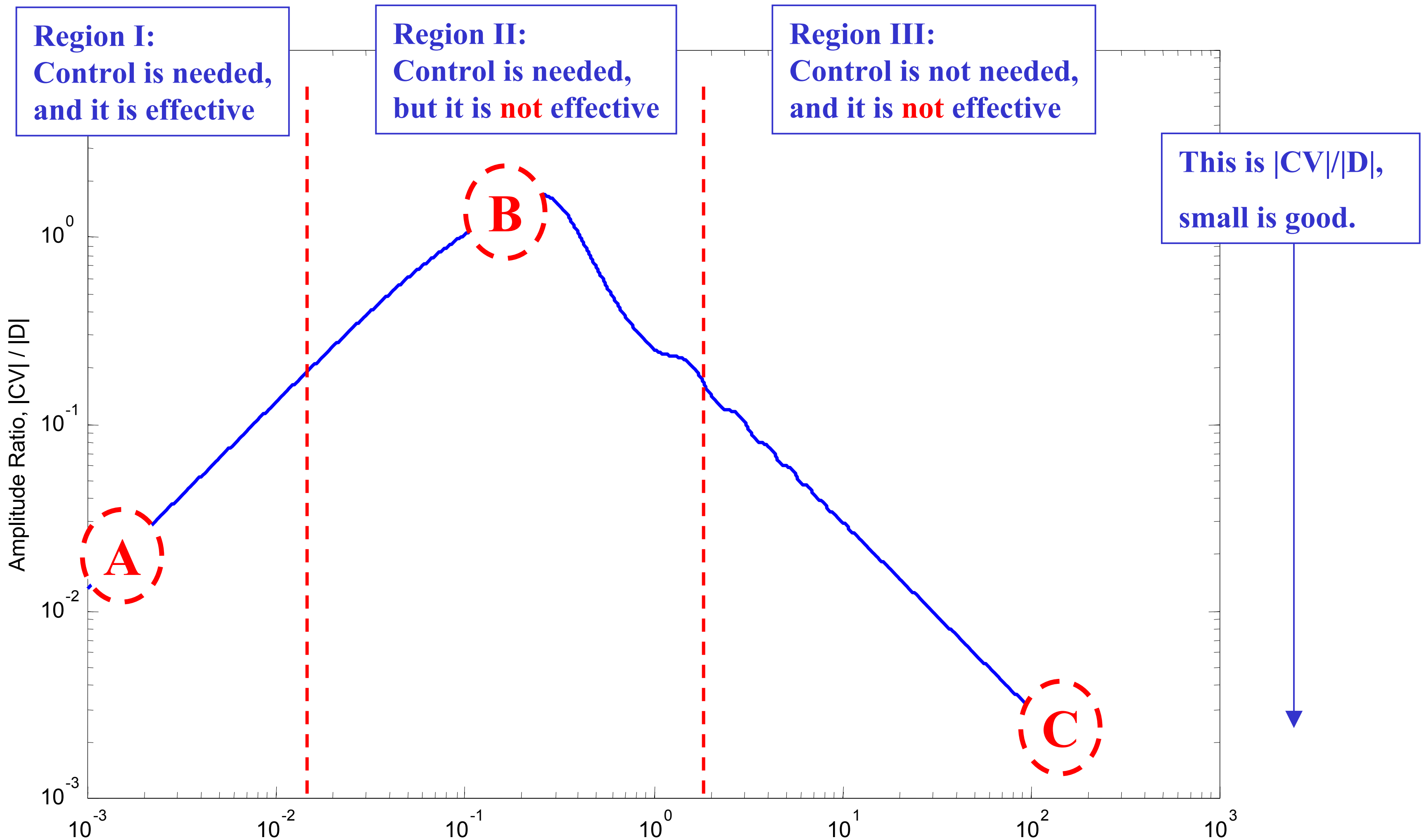
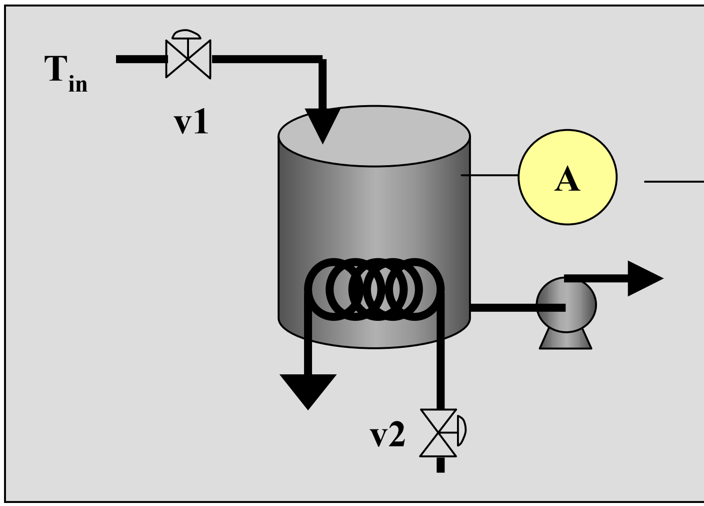
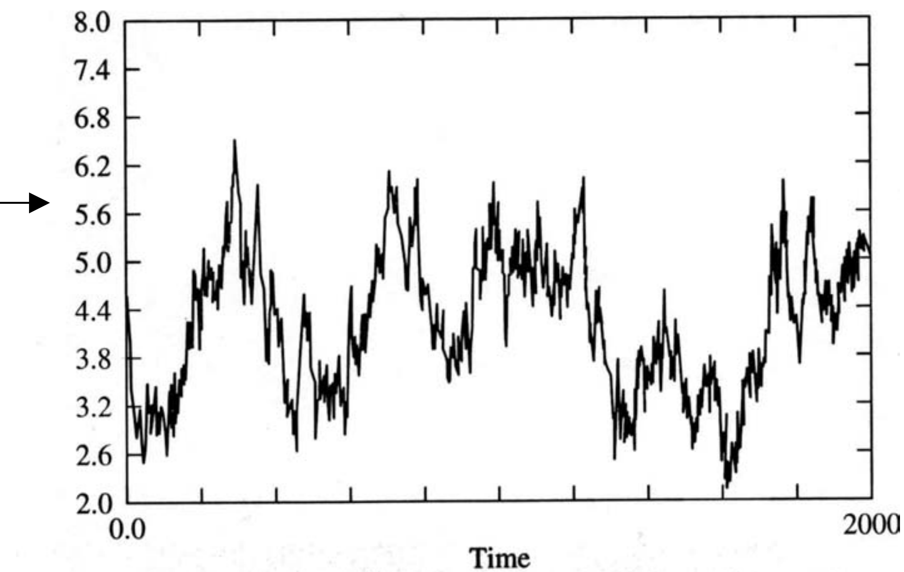


Recall, this is the disturbance frequency, low frequency = long period

CHAPTER 13: FEEDBACK PERFORMANCE

Let's apply frequency response concepts to a practical example. Can we reduce this open-loop variation?





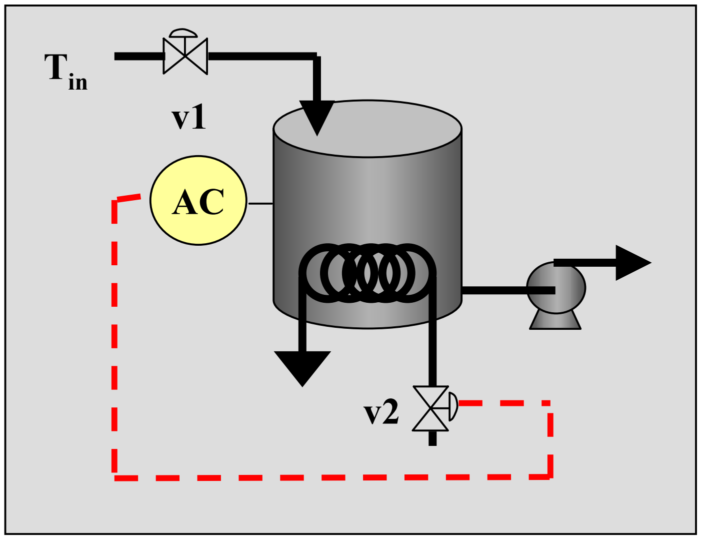
Feedback dynamics are:

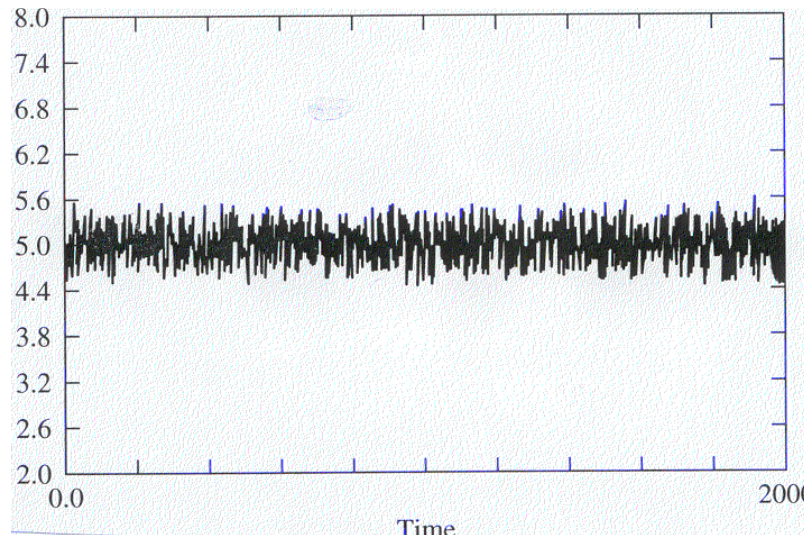
$$\frac{A(s)}{v(s)} = \frac{1.0e^{-2s}}{2s+1}$$

We note that the variation has many frequencies, some much slower than the feedback dynamics.

CHAPTER 13: FEEDBACK PERFORMANCE

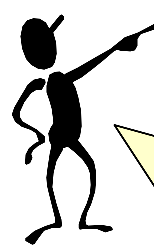
Yes, we can we reduce the variation substantially because of the dominant low frequency of the disturbance effects.





Feedback dynamics are:

$$\frac{A(s)}{v(s)} = \frac{1.0e^{-2s}}{2s+1}$$



Low frequencies reduced <u>a lot</u>.
Higher frequencies remain!

CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out

How do we calculate the frequency response?

- **We could use dynamic simulation**

  - Lots of cases at every frequency

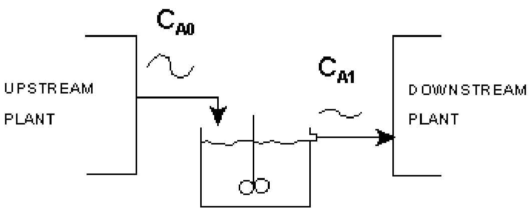
  - Can be done for non-linear systems

- **For linear models, we can use the transfer function**

  - Remember that the frequency response can be calculated by setting $s = j\,\omega$

CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out



<u>Amplitude ratio</u> = $|Y'(t)|_{max} / |X'(t)|_{max}$

For linear systems, we can evaluate directly using transfer function!
Set s = jω, with ω= frequency and j = complex variable.

$$\textbf{Amp. Ratio} = AR = |G(j\omega)| = \sqrt{\textbf{Re}(G(j\omega))^2 + \textbf{Im}(G(j\omega))^2}$$

In most programming languages, the absolute value gives the magnitude of a complex number

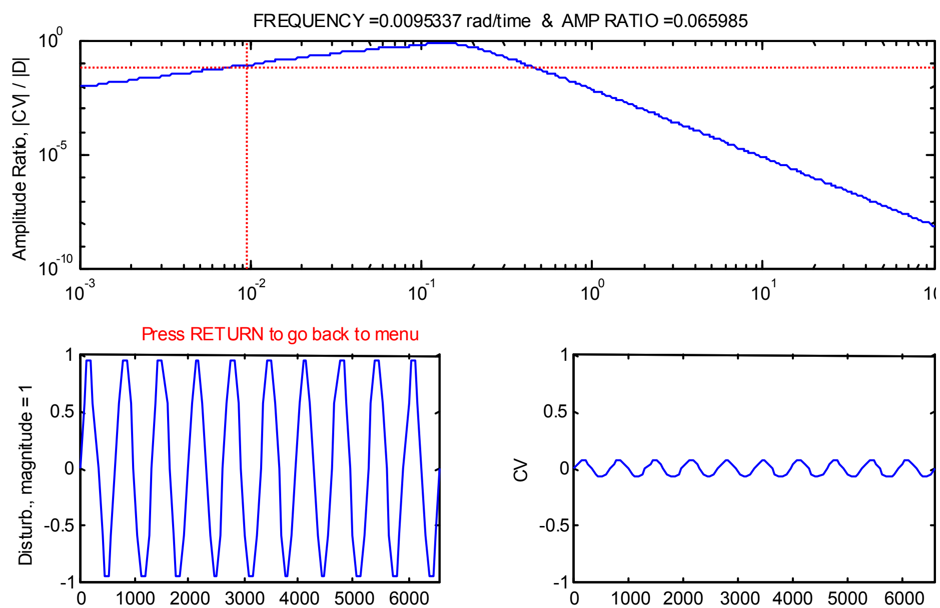
CHAPTER 13: FEEDBACK PERFORMANCE

Frequency Response : Sine in $\Rightarrow$ sine out

Caution: Do not perform these calculations by hand - too complex!

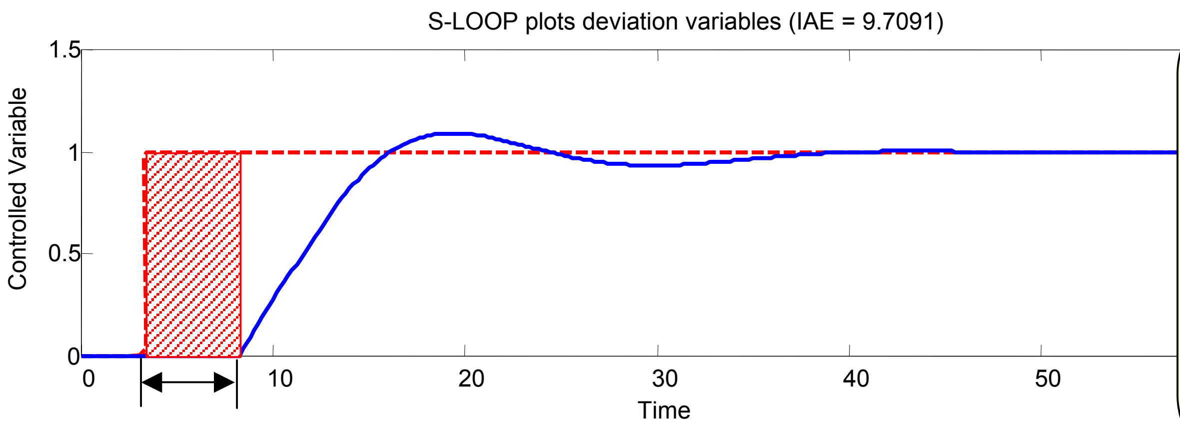
S_LOOP

For linear systems, sub-menu 7 gives Bode plot and sines at user-selected frequency

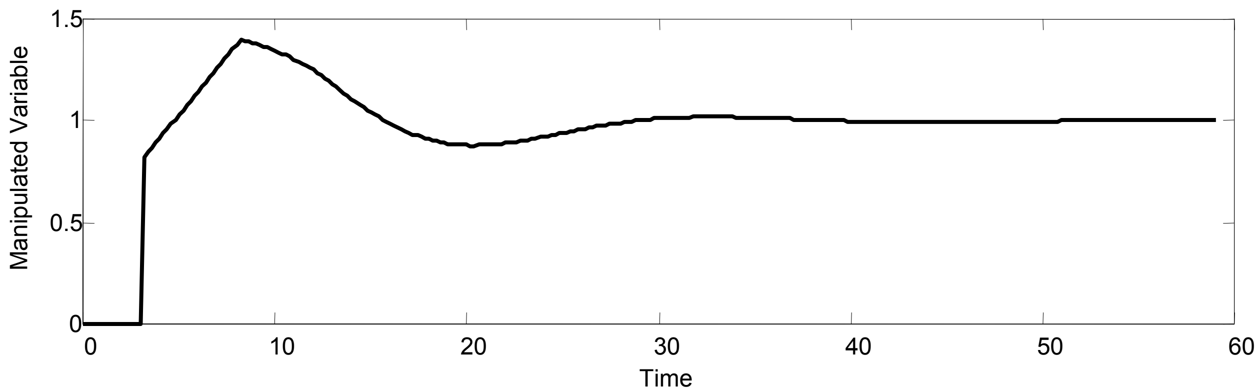


CHAPTER 13: FEEDBACK PERFORMANCE

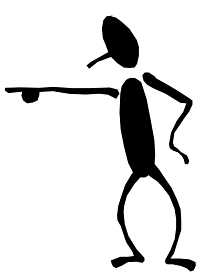
Performance Observation #1. **Feedback dead time limits best possible performance**



θ_p, feedback dead time

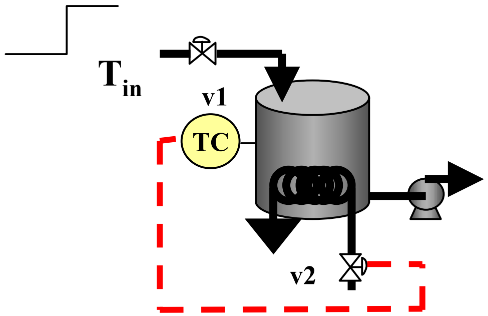


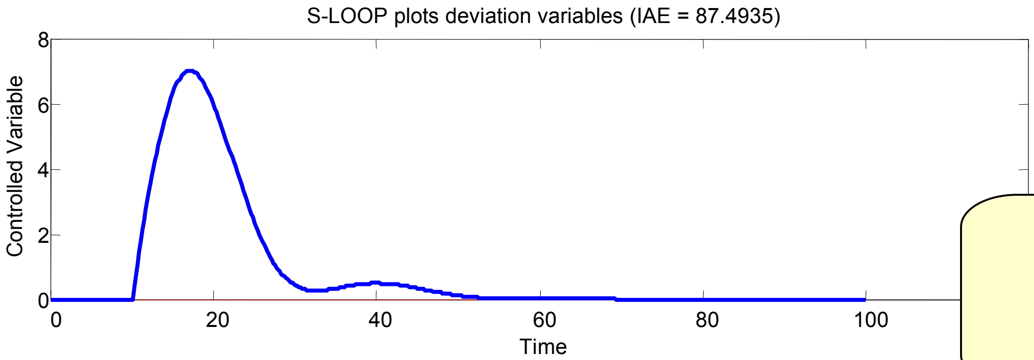
Discuss why the red box defines deviation from set point that cannot be reduced by any feedback.

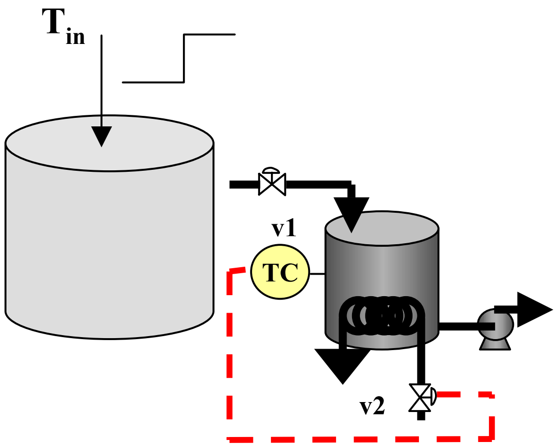


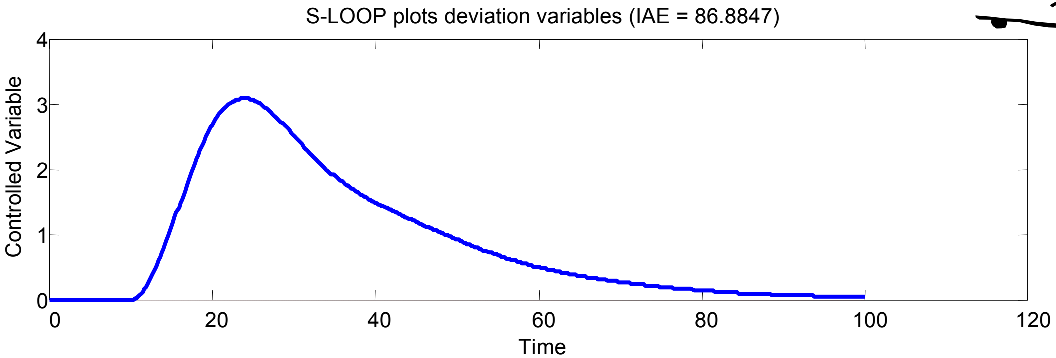
CHAPTER 13: FEEDBACK PERFORMANCE

Performance Observation #2. Large disturbance time constants slow disturbances and improve performance.





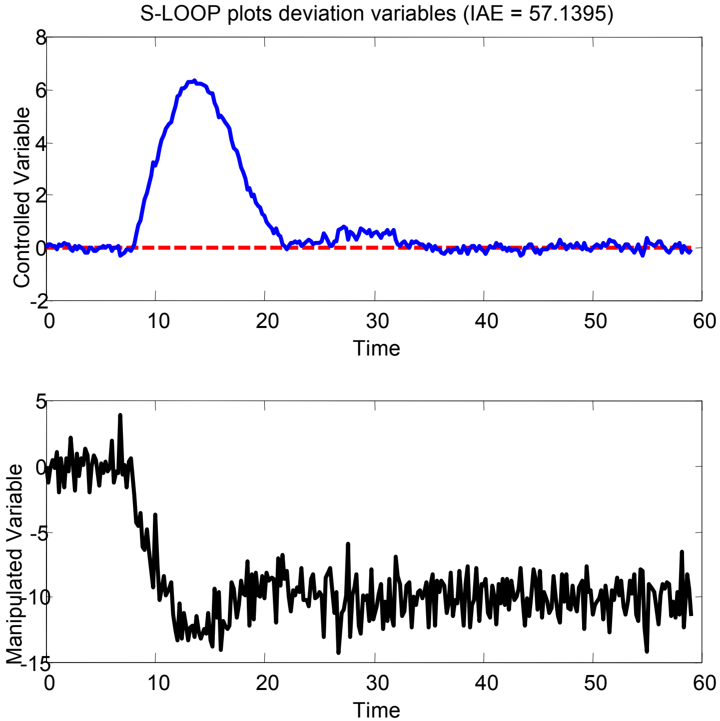




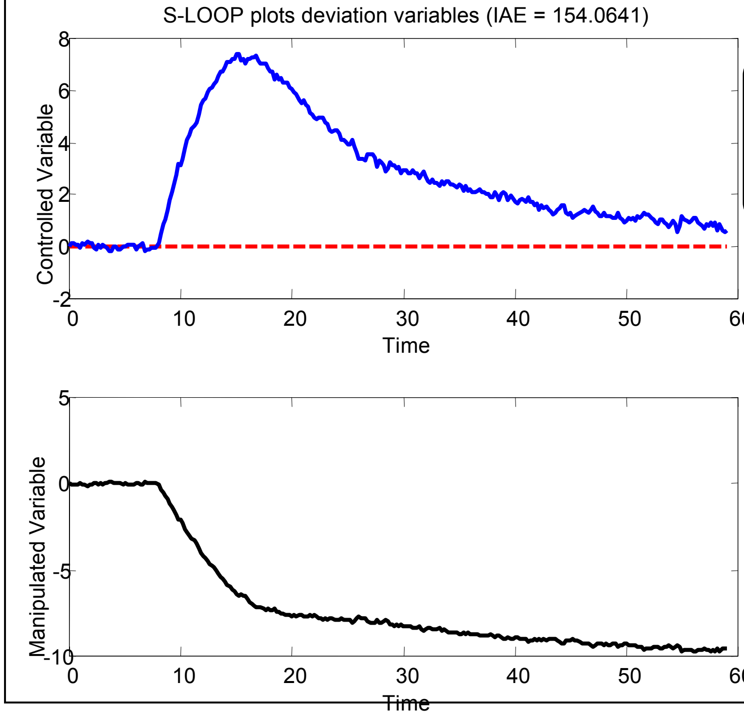
CHAPTER 13: FEEDBACK PERFORMANCE

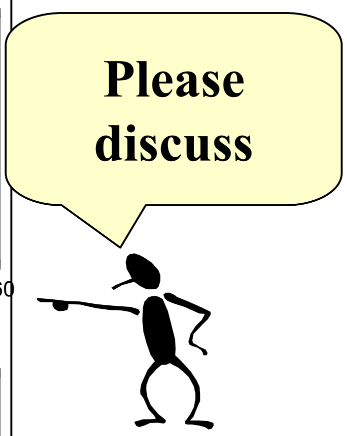
Performance Observation #3. Feedback must change the MV aggressively to improve performance.

Kc = 1.3, TI = 7, Td = 1.5



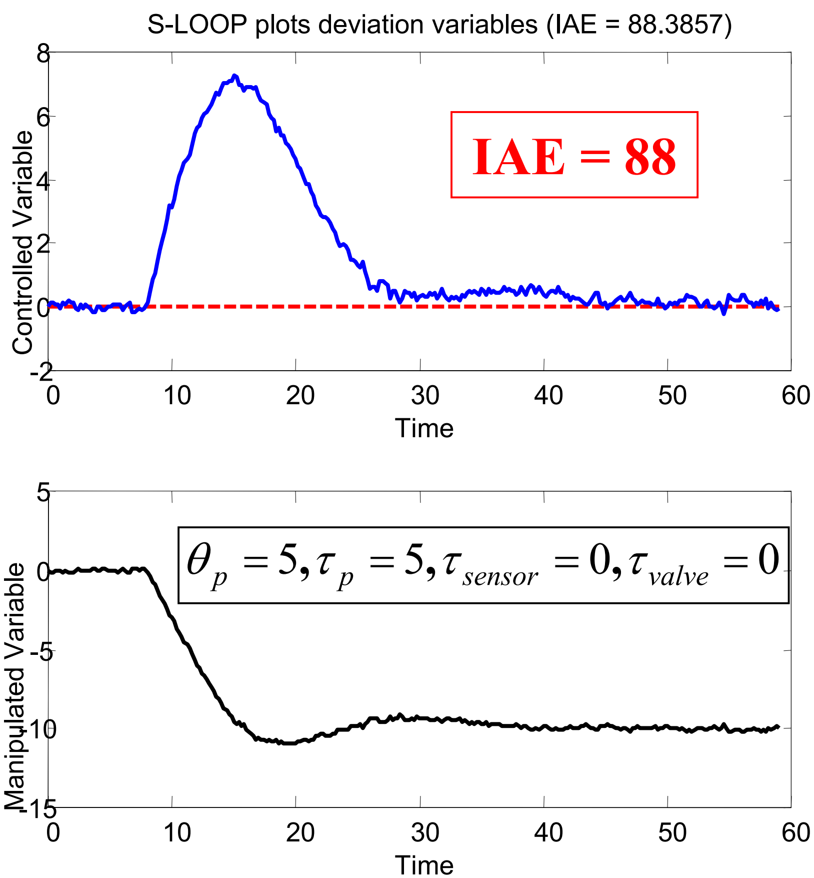
Kc = 0.6, TI = 10, Td = 0

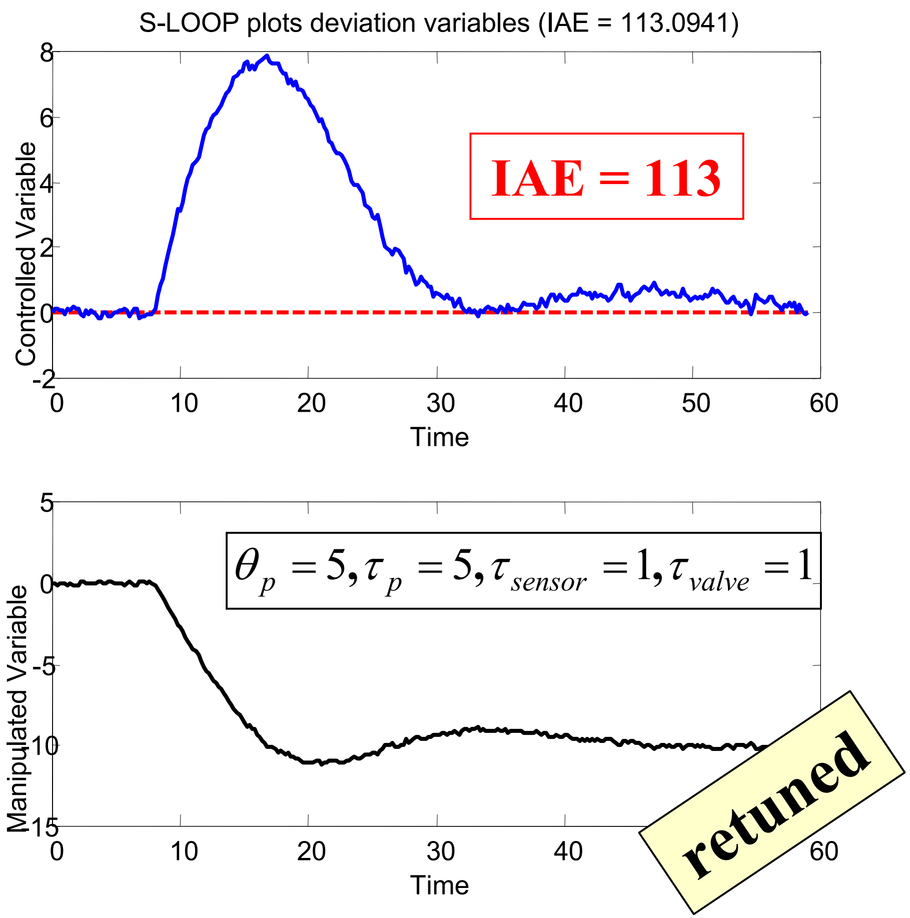




CHAPTER 13: FEEDBACK PERFORMANCE

Performance Observation #4. Sensor and final element dynamics also degrade performance.





CHAPTER 13: FEEDBACK PERFORMANCE

QUICK SUMMARY OF KEY POINTS
Important general insights!!

Class exercise:

- **The importance of disturbance dynamics**

- **The importance of feedback dynamics**

- **The importance of the disturbance frequency**

CHAPTER 13: FEEDBACK PERFORMANCE

QUICK SUMMARY OF KEY POINTS
Important general insights!!

- **The importance of disturbance dynamics**

  - Large time constants decrease the effect of the disturbance on the controller variable

  - Dead time has no effect

- **The importance of feedback dynamics**

  - Large dead times and time constants are bad!!

- **The importance of the disturbance frequency**

  - Low frequencies are easy to control. Critical frequency cannot be controlled.

CHAPTER 13: FEEDBACK PERFORMANCE

KEY CONCLUSION ABOUT FEEDBACK CONTROL!!

Class exercise: We can achieve the desired control performance by a judicious selection of controller algorithms and tuning.

- [ ] **True**
- [ ] **False**

CHAPTER 13: FEEDBACK PERFORMANCE

KEY CONCLUSION ABOUT FEEDBACK CONTROL!!

FALSE!

FEEDBACK CONTROL PERFORMANCE IS LIMITED

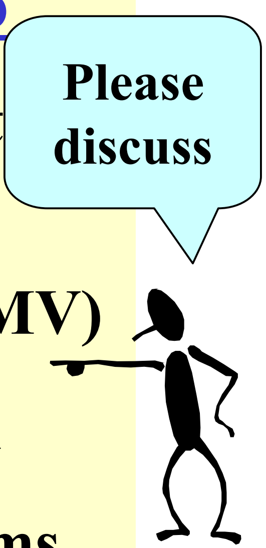
- **The process dynamics introduce limits on the best achievable feedback performance**

- **No controller algorithm can do better (same CV-MV)**

- **Controller tuning cannot overcome this limitation**

- **The PID often performs well for single-loop systems**

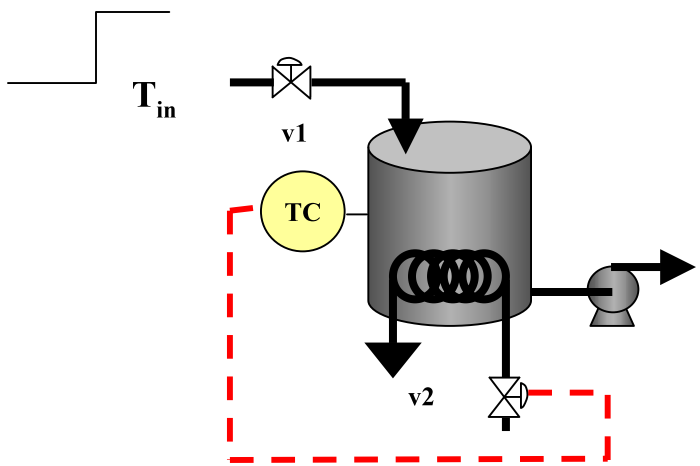
- **If we need better performance, we must change the process or the control structure (See upcoming chapters)**

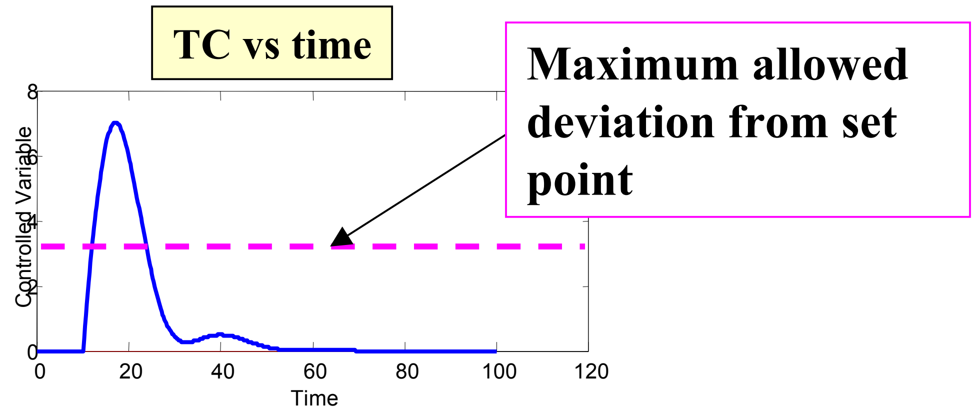


CHAPTER 13: FEEDBACK PERFORMANCE

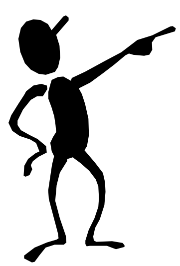
STEPS TO IMPROVE FEEDBACK PERFORMANCE!!

Class exercise:



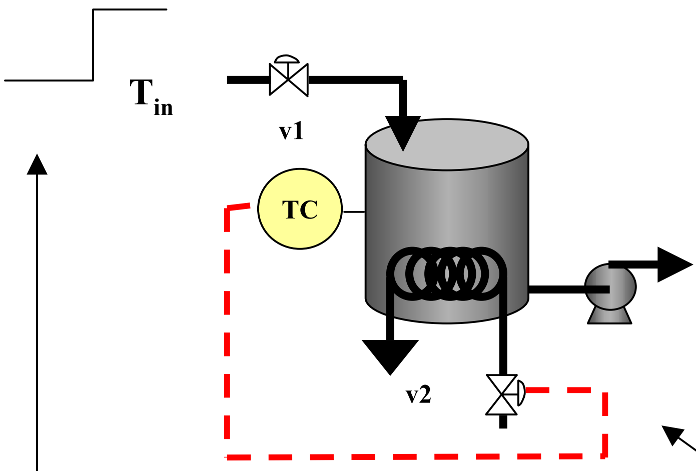


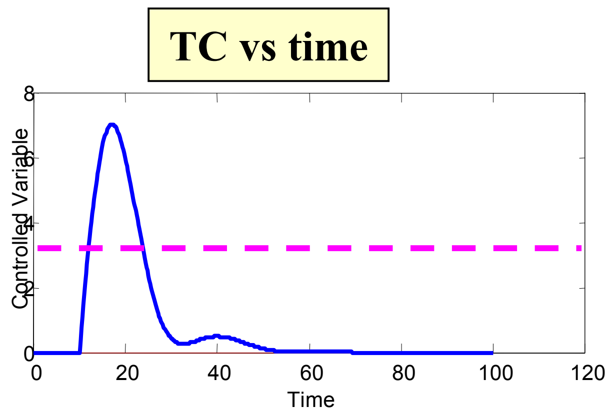
How do we improve control performance?



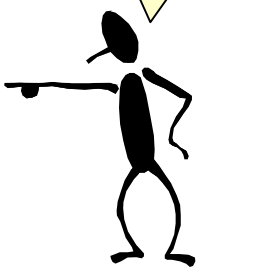
CHAPTER 13: FEEDBACK PERFORMANCE

STEPS TO IMPROVE FEEDBACK PERFORMANCE!!





Also,
see the next
few chapters!



Reduce disturbance effect by looking "upstream", if possible

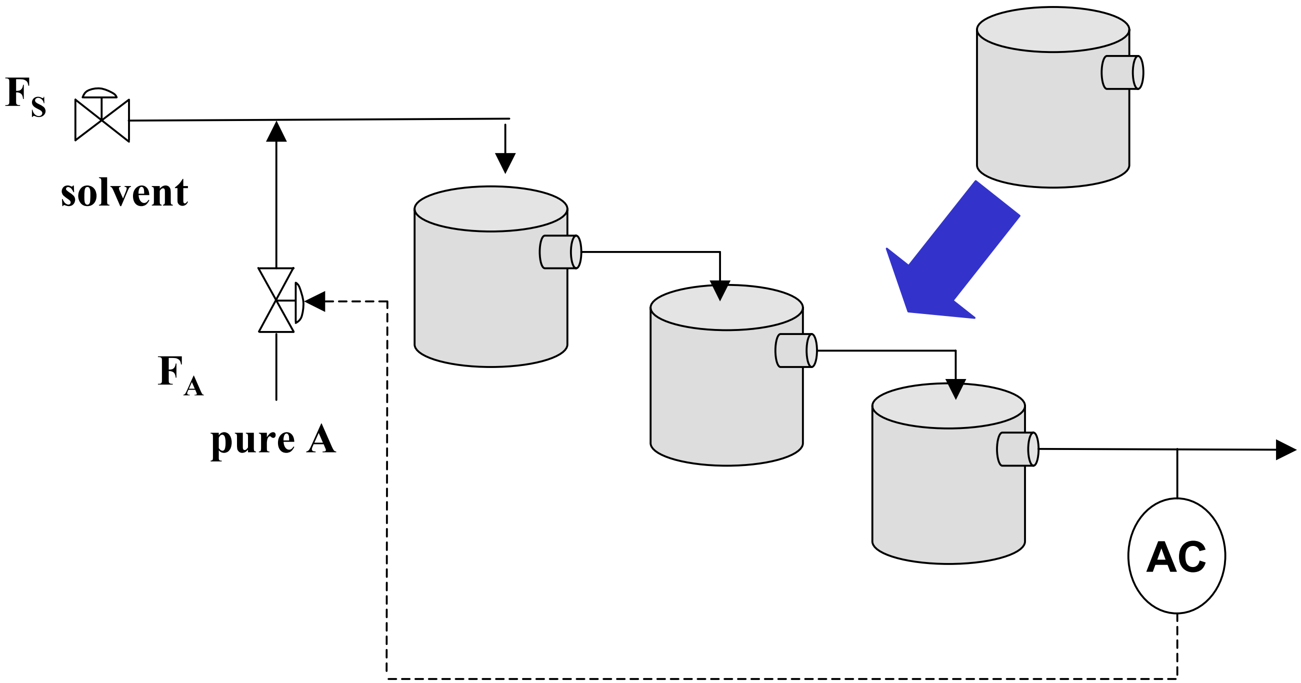
- **Reduce the magnitude**
- **Increase time constant (tank)**

Improve feedback dynamics, if possible

- **Reduce dead time & time constants**

CHAPTER 13: FB PERFORMANCE WORKSHOP 1

The PID controller has been applied to a three-tank mixer. We have decided to include another mixing tank in the process. How will the performance be changed?



$K_c = 30$

$T_I = 11$

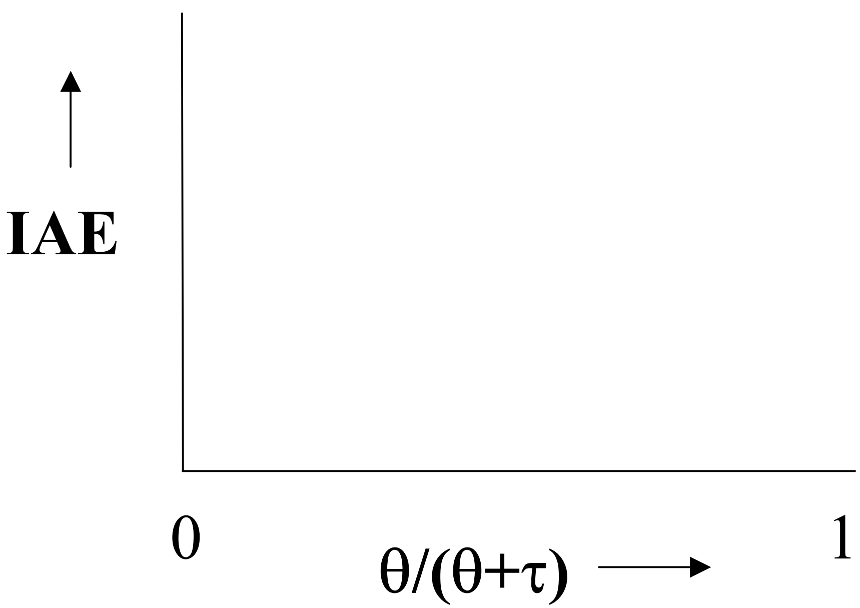
$T_d = 0.8$

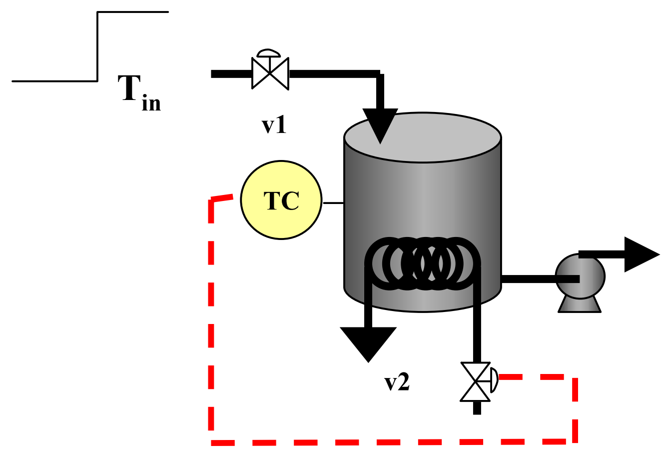
CHAPTER 13: FB PERFORMANCE WORKSHOP 2

Sketch the shape of feedback control performance vs. the feedback fraction dead time, $\theta/(\theta+\tau)$. Assume disturbance time constant is the same as the feedback time constant.

1. **The performance with the best PID tuning**

2. **The best possible feedback**





CHAPTER 13: FB PERFORMANCE WORKSHOP 3

The transfer function below gives the behavior of the controlled variables, CV, in response to a disturbance. As we increase the controller gain to a large number, the controlled variable deviation can be made as small as desired in the frequency response calculation.

Is this result reasonable? Why?

<u>Disturbance Response</u>

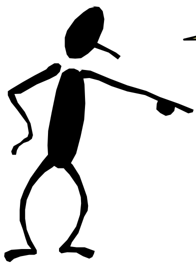
$$\frac{CV(s)}{D(s)} = \frac{G_d(s)}{1 + K_c G_p(s) G_v(s) G_S(s)}$$

CHAPTER 13: FB PERFORMANCE WORKSHOP 4

Determine a rough estimate of the dynamics for the following control-loop elements.

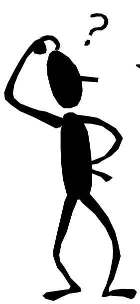
- **Thermocouple in a steel thermowell**
- **Globe valve with pneumatic actuator**
- **Pressure sensor**
- **Gas chromatograph on a sample from a gas stream**
- **Signal transmission for 400 m**
- **Typical commercial digital controller execution period**

CHAPTER 13: PERFORMANCE



When I complete this chapter, I want to be able to do the following.

- Apply two methods for evaluating control performance: simulation and frequency response
- Apply general guidelines for the effect of
  - feedback dead time
  - disturbance time constant
  - MV variability
  - sensor and final element dynamics



Lot's of improvement, but we need some more study!

- Read the textbook
- Review the notes, especially learning goals and workshop
- Try out the self-study suggestions
- Naturally, we'll have an assignment!

CHAPTER 13: LEARNING RESOURCES

- **SITE PC-EDUCATION WEB**
  - Instrumentation Notes
  - Interactive Learning Module
    (Chapter 13, not yet available)
  - Tutorials (Chapter 13)

- **S_LOOP**
  - Dynamic simulation of linear system
  - Easy evaluation of frequency response for open and closed-loop systems. Compare Bode plot with sine plots!

CHAPTER 13: SUGGESTIONS FOR SELF-STUDY

1. **Carefully review the summary in textbook Table 13.3. Do not memorize, but understand!**

2. **Use S_LOOP to simulate the system in Workshop Question #1.**

3. **Derive a mathematical expression for the <u>minimum IAE</u> for a feedback loop responding to a single step set point change. Hint: See textbook equation (13.8) and associated discussion.**

4. **Discuss the information that you need to know to be able to predict the performance, i.e., the behavior of the CV and MV.**

CHAPTER 13: SUGGESTIONS FOR SELF-STUDY

5. **S_LOOP: Consider the system used in Performance Observation #1 ($K_p = 1$, $\theta_p = 5$, $\tau_p = 5$; $K_d = 1.5$ $\tau_d = 5$). Simulate the closed-loop dynamic response for a step disturbance of magnitude 1.**

   - **How did you tune the PID controller?**
   - **Sketch the best possible CV control performance on the plot of the transient response.**
   - **What steps are required to improve the CV performance?**

6. **Develop two more Performance Observations and prepare one visual aids (slide) per observation to explain them to your class.**