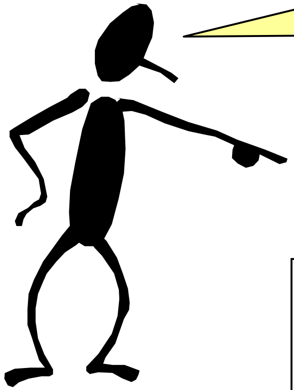
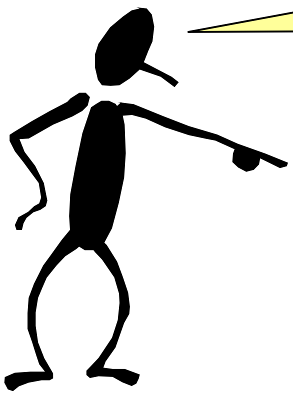
CHAPTER 9: PID TUNING



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

- Explain the performance goals that we seek to achieve via tuning.
- Apply a tuning procedure using the process reaction curve and tuning correlations.
- Further improve performance by fine tuning

CHAPTER 9: PID TUNING



Outline of the lesson.

- A trial and error approach - why we don’t use it
- Define the tuning problem
- Solve and develop correlations
- Apply correlations to examples
- Fine tune - the personal touch

CHAPTER 9: PID TUNING

PROPERTIES THAT WE SEEK IN A CONTROLLER

- **Good Performance** - feedback measures from Chapter 7
- **Wide applicability** - adjustable parameters

This chapter

- **Timely calculations** - avoid convergence loops
- **Switch to/from manual** - bumplessly

Previous chapter

- **Extensible** - enhanced easily

Later chapters

CHAPTER 9: PID TUNING

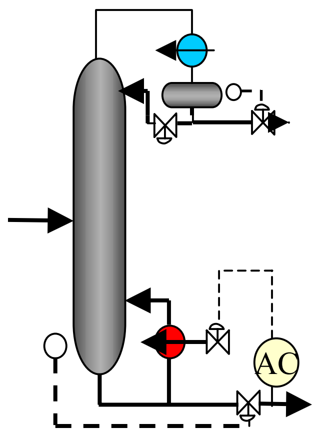
- **How do we apply the same equation to many processes?**
- **How to achieve the dynamic performance that we desire?**

TUNING!!!

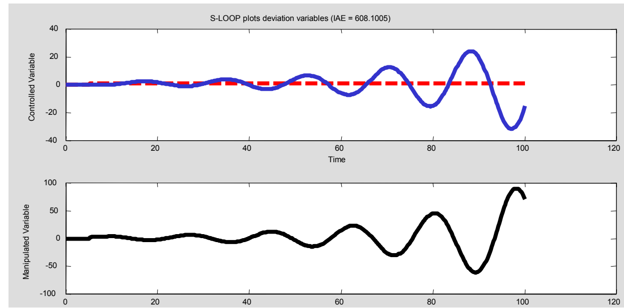
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')\,dt' - T_d \frac{d\,CV}{dt} \right] + I$$

The adjustable parameters are called <u>tuning constants</u>. We can match the values to the process to affect the dynamic performance

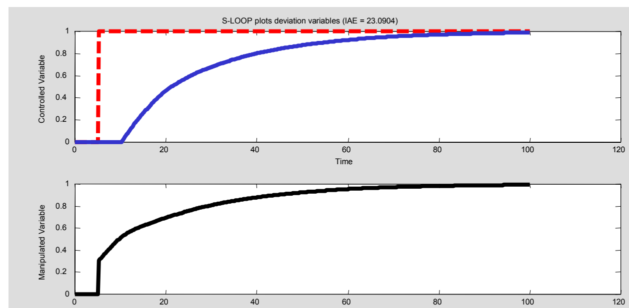
CHAPTER 9: PID TUNING



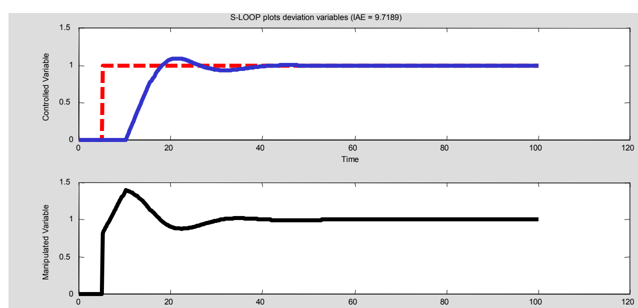
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')dt' - T_d \frac{d\,CV}{dt} \right] + I$$



Trial 1: unstable, lost \$25,000

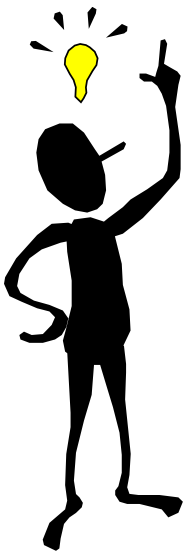


Trial 2: too slow, lost \$3,000

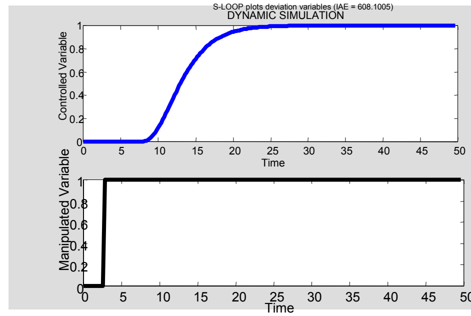


Trial n: OK, finally, but took way too long!!

CHAPTER 9: PID TUNING



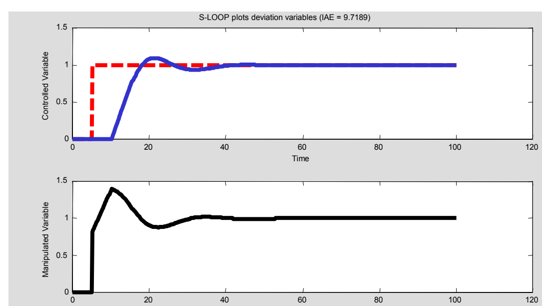
Yes, we can prepare good correlations!



Determine a model using the process reaction curve experiment.

Kc TI

Determine the initial tuning constants from a correlation.



Apply and fine tune as needed.

<u>**Define the tuning problem**</u>

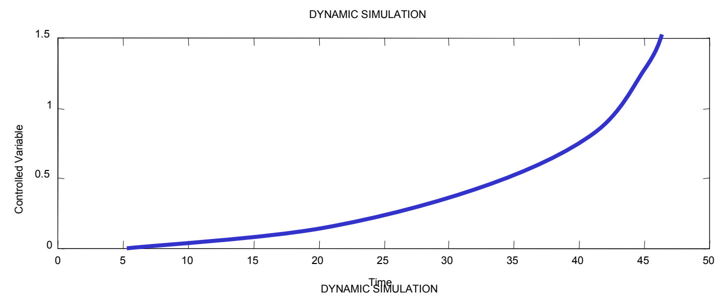
1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

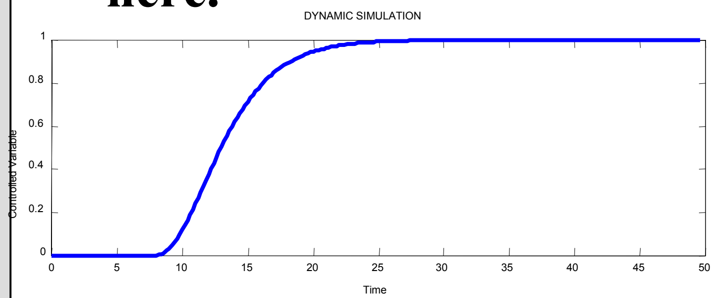
CHAPTER 9: PID TUNING

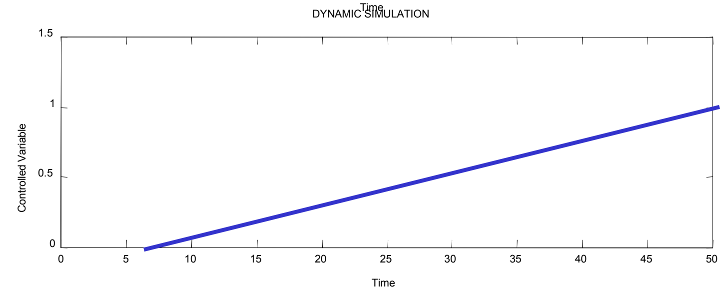
<u>Define the tuning problem</u>

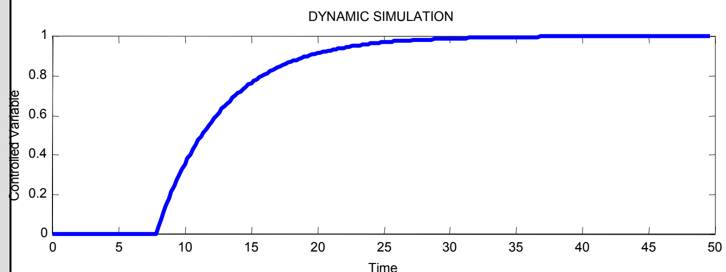
1. Process Dynamics →
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

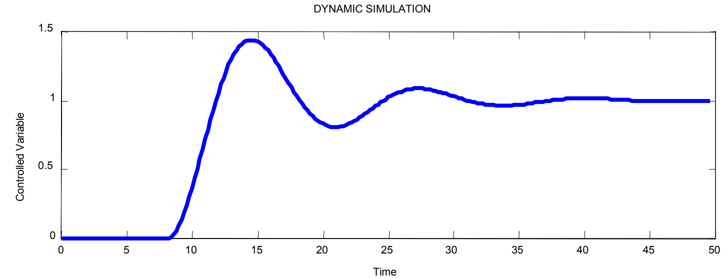
The PID controller will function successfully for the wide range of feedback process dynamics shown here.

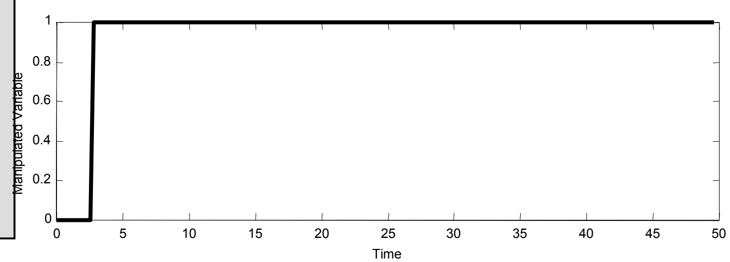


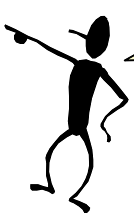












Describe the dynamics from the step change data.

CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
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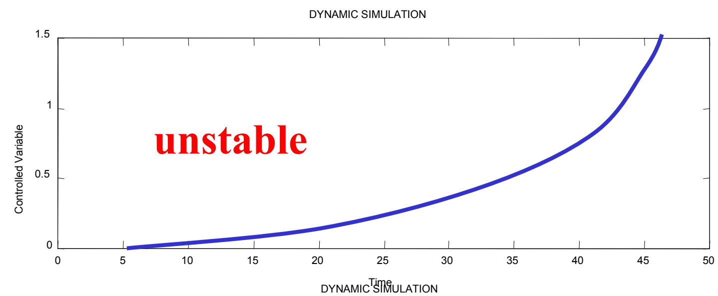
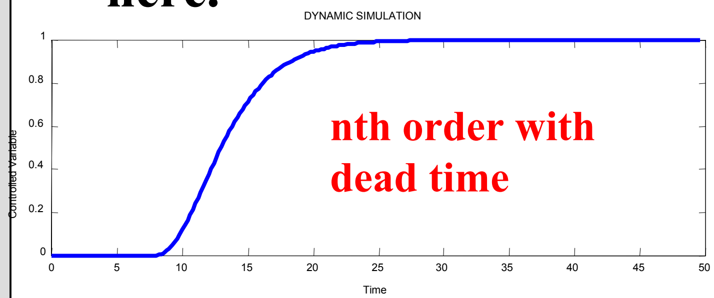
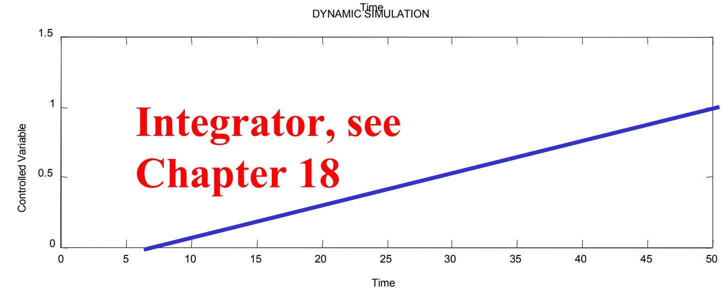
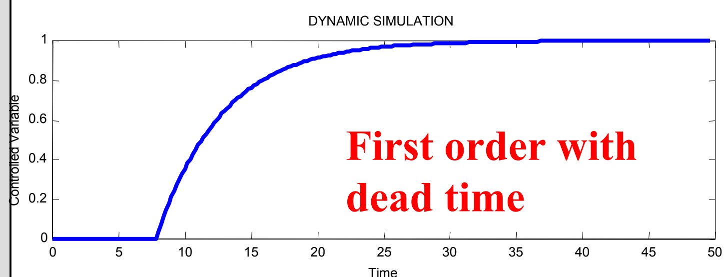
5. Controller
6. Performance measures

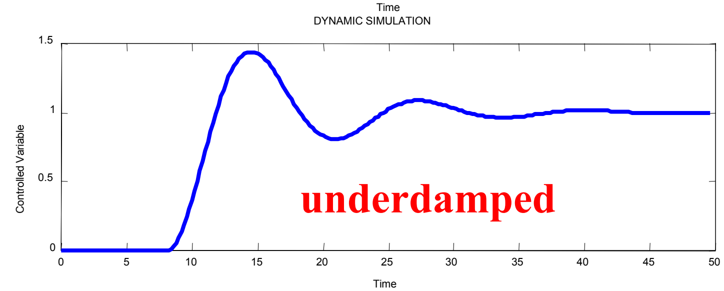
The PID controller will function successfully for the wide range of feedback process dynamics shown here.

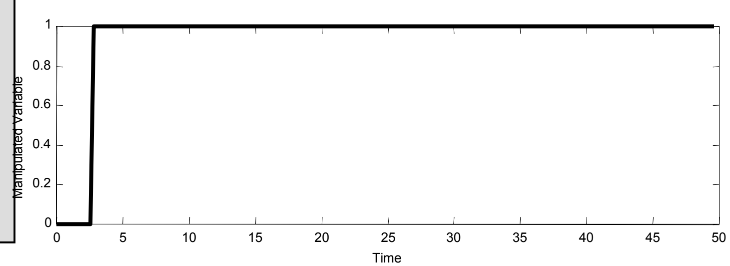


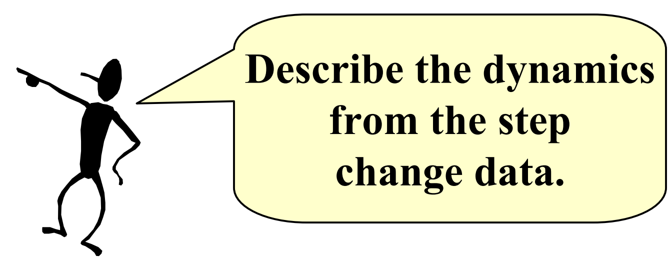










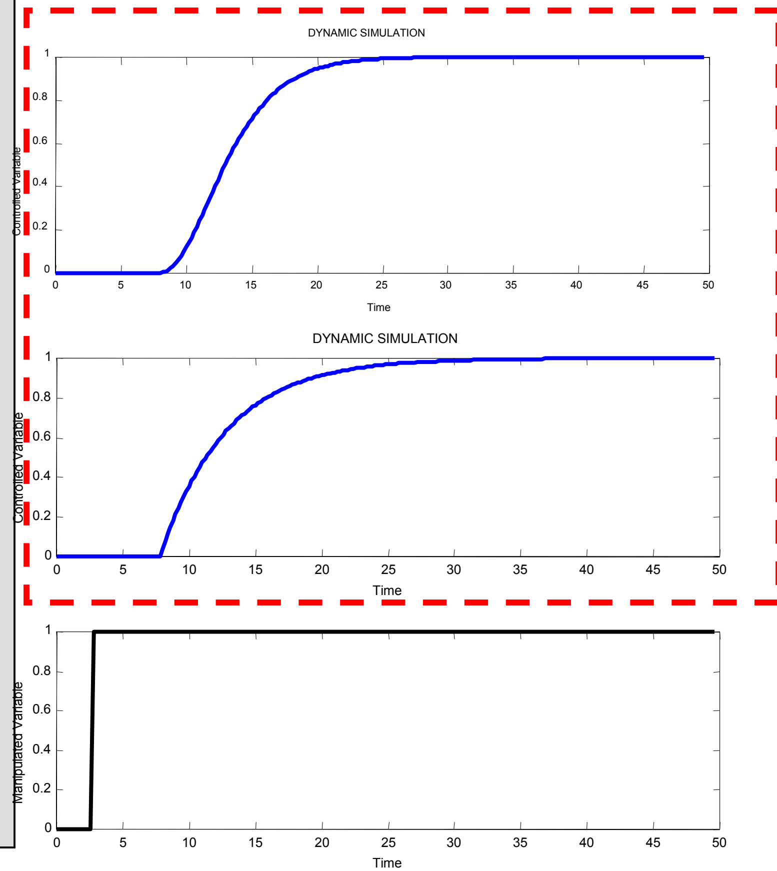


CHAPTER 9: PID TUNING

<u>**Define the tuning problem**</u>

1. **Process Dynamics** →
2. **Measured variable**
3. **Model error**
4. **Input forcing**
5. **Controller**
6. **Performance measures**

The PID controller will function successfully for a wide range of feedback process dynamics



We will develop <u>tuning correlations</u> for these dynamics.

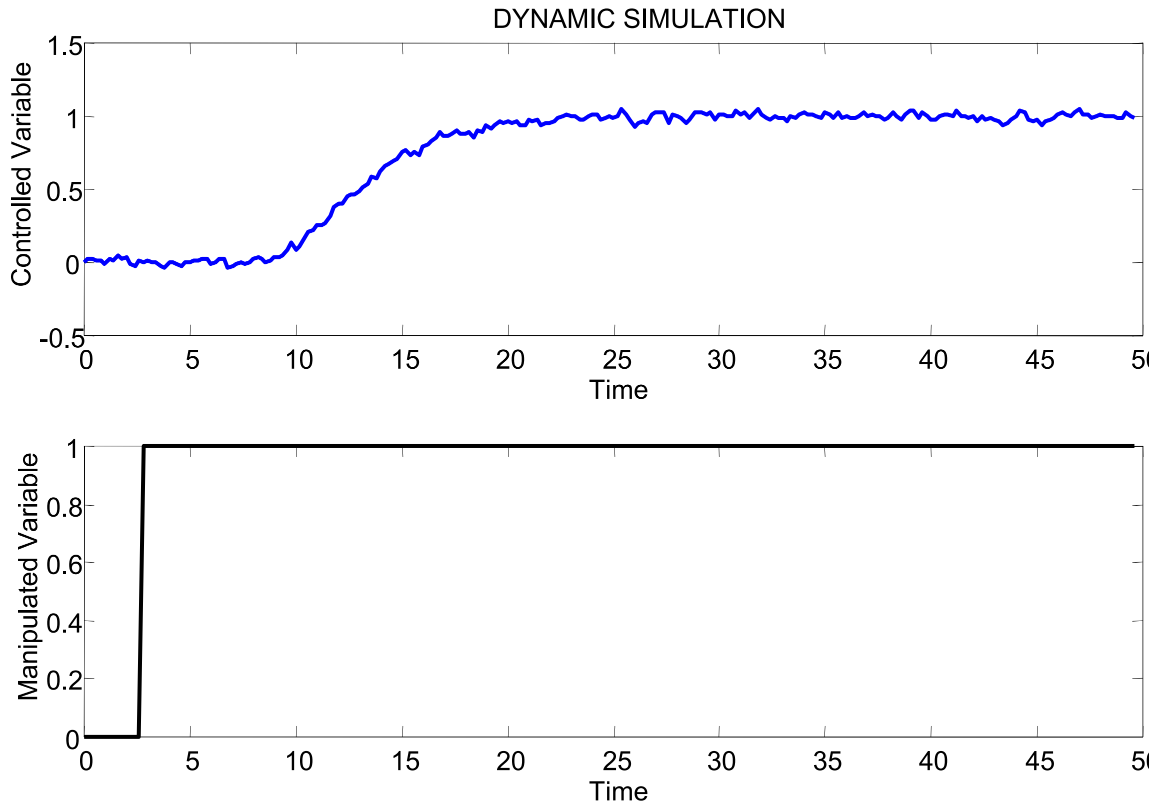
- **Most commonly occurring**
- **Fit model using process reaction curve**
- **Other processes can be controlled with PID; need more trial and error**

CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

Realistic situation: The measured variable will include the effects of sensor noise and higher frequency process disturbances.

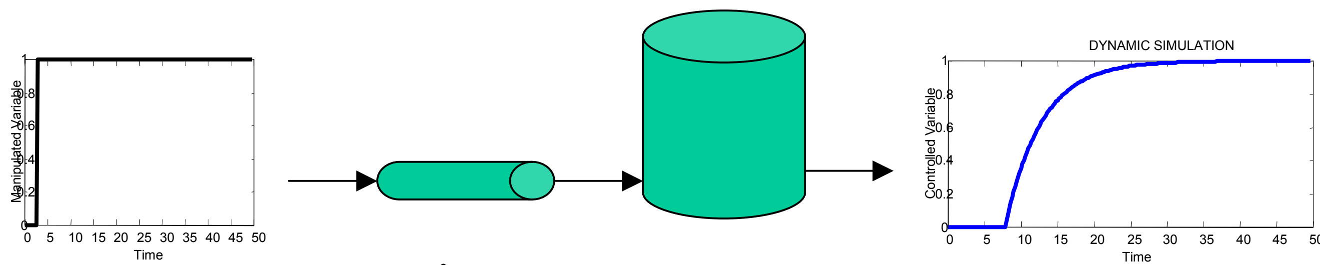


CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

Realistic situation: **The model does not represent the process exactly. We will assume that the model has ± 25% errors in gain, time constant and dead time, for example:**



gain

1.5 - 2.5

Dead time

3.75 - 6.25

$$G_P(s) = \frac{CV(s)}{MV(s)} = \frac{2.0 e^{-5\,s}}{10\,\mathbf{s}+\mathbf{1}}$$

Time constant

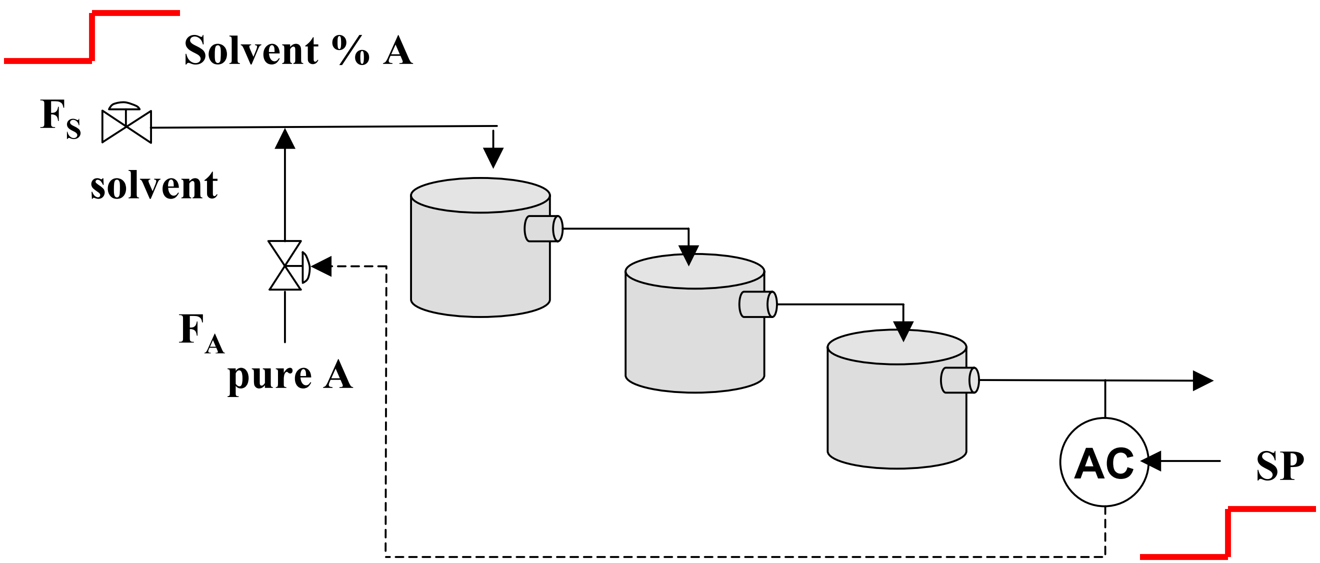
7.5 -1 2.5

CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

Realistic situation: Two typical inputs will be considered, changes in set point and disturbance. For correlations, step inputs, but controller will function for other inputs.



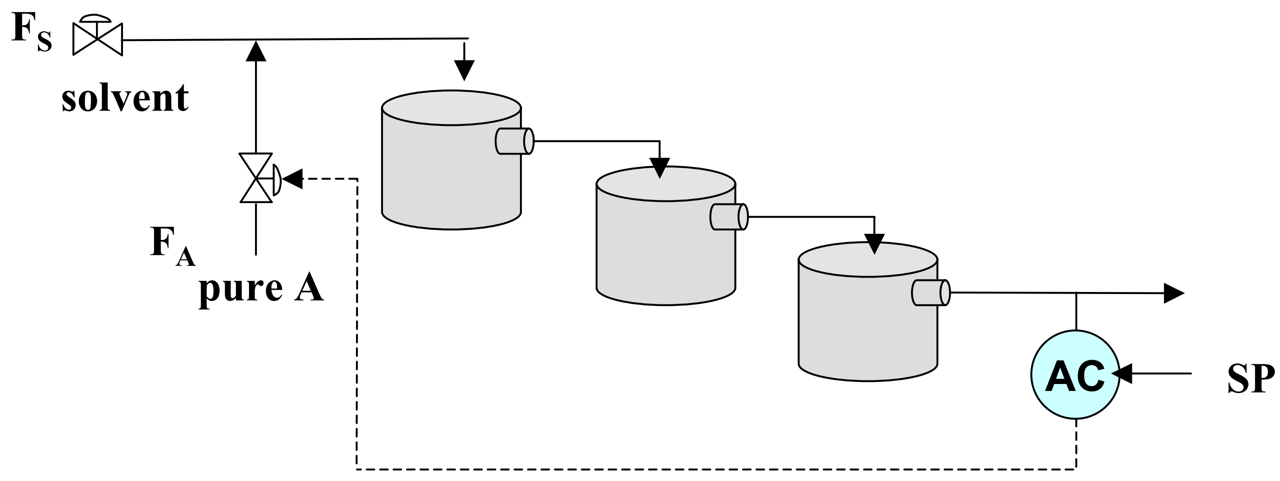
CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

Realistic situation: We will consider the **PID controller**, which is used for nearly all single-loop (1CV, 1MV) controllers.

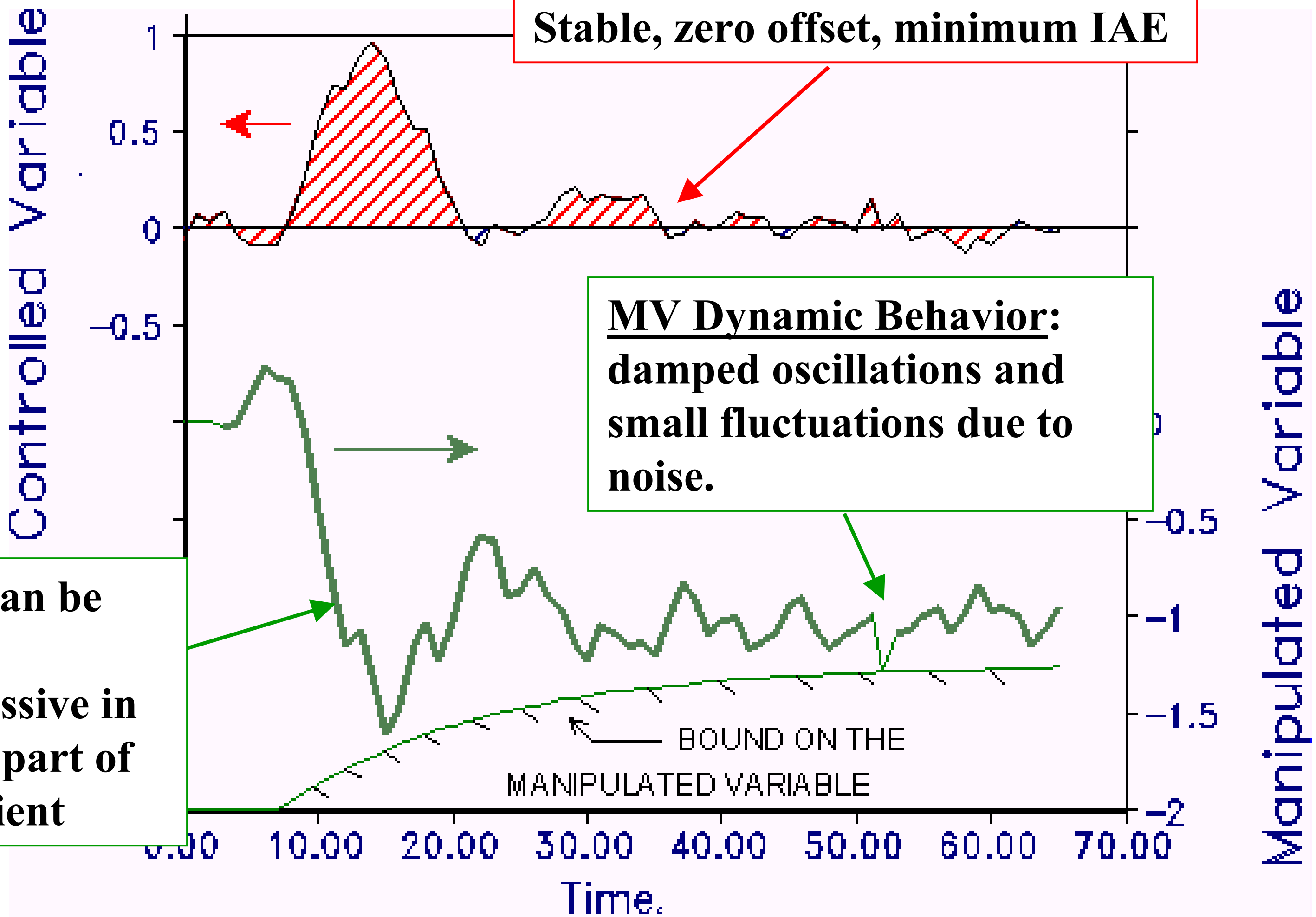
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')dt' - T_d \frac{d\,CV}{dt} \right] + I$$



CHAPTER 9: PID TUNING

<u>Define the tuning problem</u>

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forci
5. Controller
6. Performance measures



<u>CV Dynamic Behavior</u>: Stable, zero offset, minimum IAE

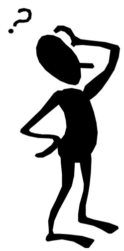
<u>MV Dynamic Behavior</u>: damped oscillations and small fluctuations due to noise.

<u>MV</u> can be more aggressive in early part of transient

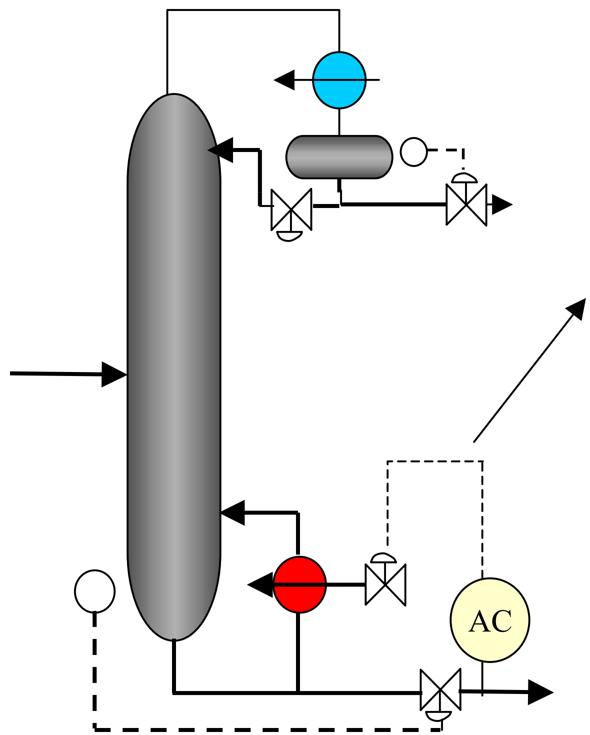
CHAPTER 9: PID TUNING

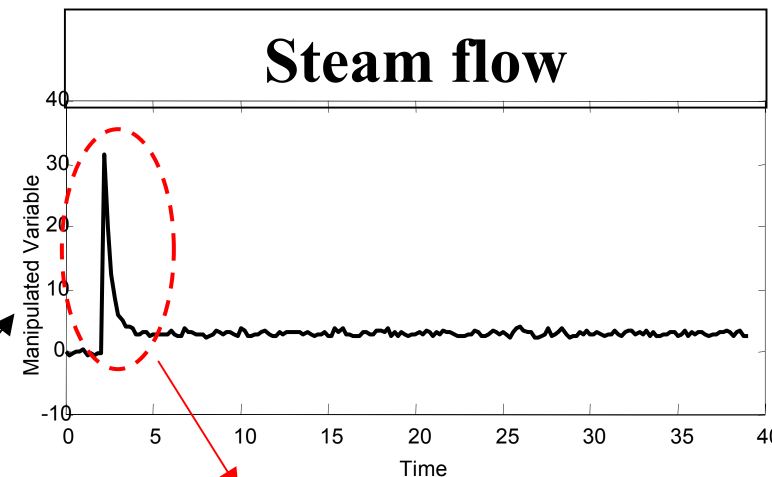
Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures



Our primary goal is to maintain the CV near the set point. Besides not wearing out the valve, why do we have goals for the MV?



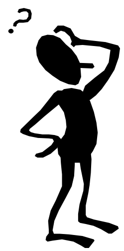


Large, rapid changes to the steam flow can damage the trays

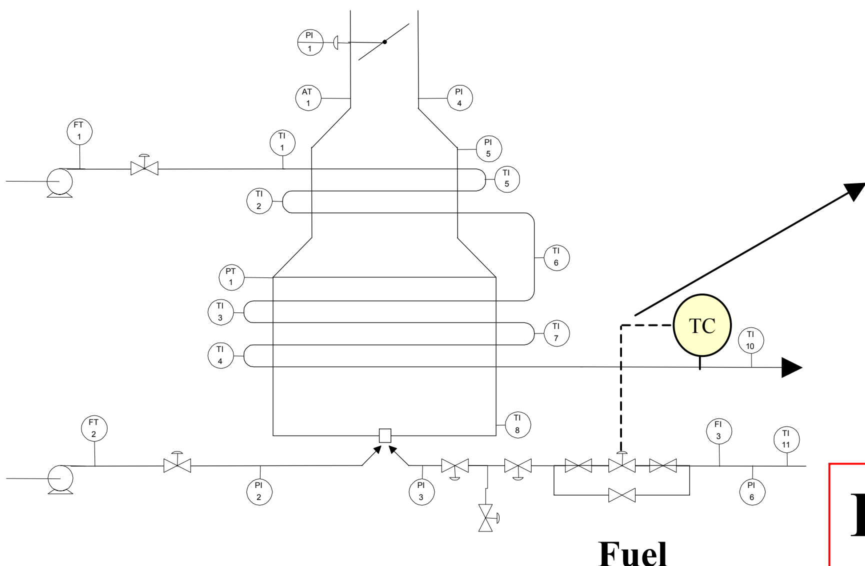
CHAPTER 9: PID TUNING

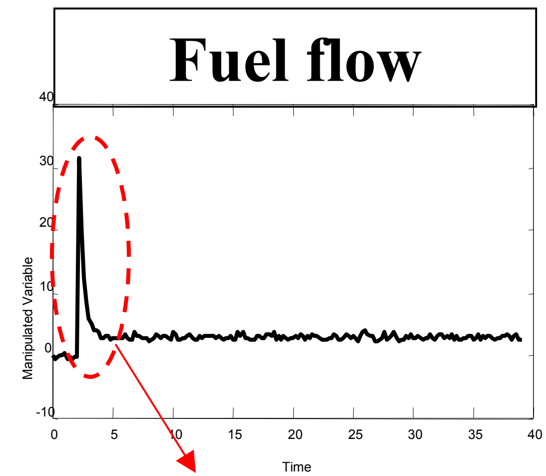
Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures



Our primary goal is to maintain the CV near the set point. Besides not wearing out the valve, why do we have goals for the MV?





Large, rapid changes to the fuel flow cause thermal stress that damages tubes.

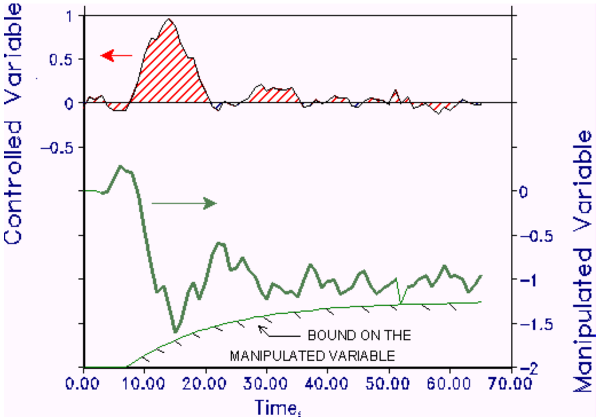
CHAPTER 9: PID TUNING

Define the tuning problem

1. Process Dynamics
2. Measured variable
3. Model error
4. Input forcing
5. Controller
6. Performance measures

COMBINED DEFINITION OF TUNING PROBLEM FOR CORRELATION

- First order with dead time process model
- Noisy measurement signal
- ± 25% parameters errors between model/plant
- PID controller: determine K_c, T_I, T_d
- Minimize IAE with MV inside bound

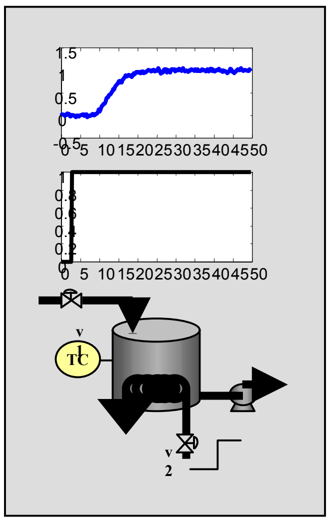


We achieve the goals by adjusting Kc, TI and Td.

Details in chapter and Appendix E.

CHAPTER 9: PID TUNING

Process reaction curve



$K_p = 1$

$\theta = 5$

$\tau = 5$

Solve the tuning problem. Requires a computer program.

COMBINED DEFINITION OF TUNING

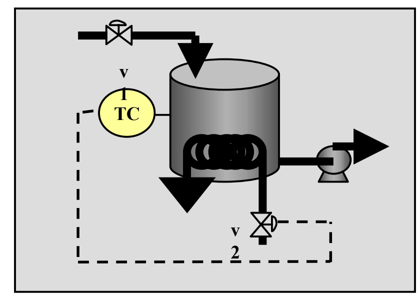
- First order with dead time process model
- Noisy measurement signal
- ± 25% parameters errors between model/plant
- PID controller: determine K_c, T_I, T_d
- Minimize IAE with MV inside bound

$K_c = 0.74$

$TI = 7.5$

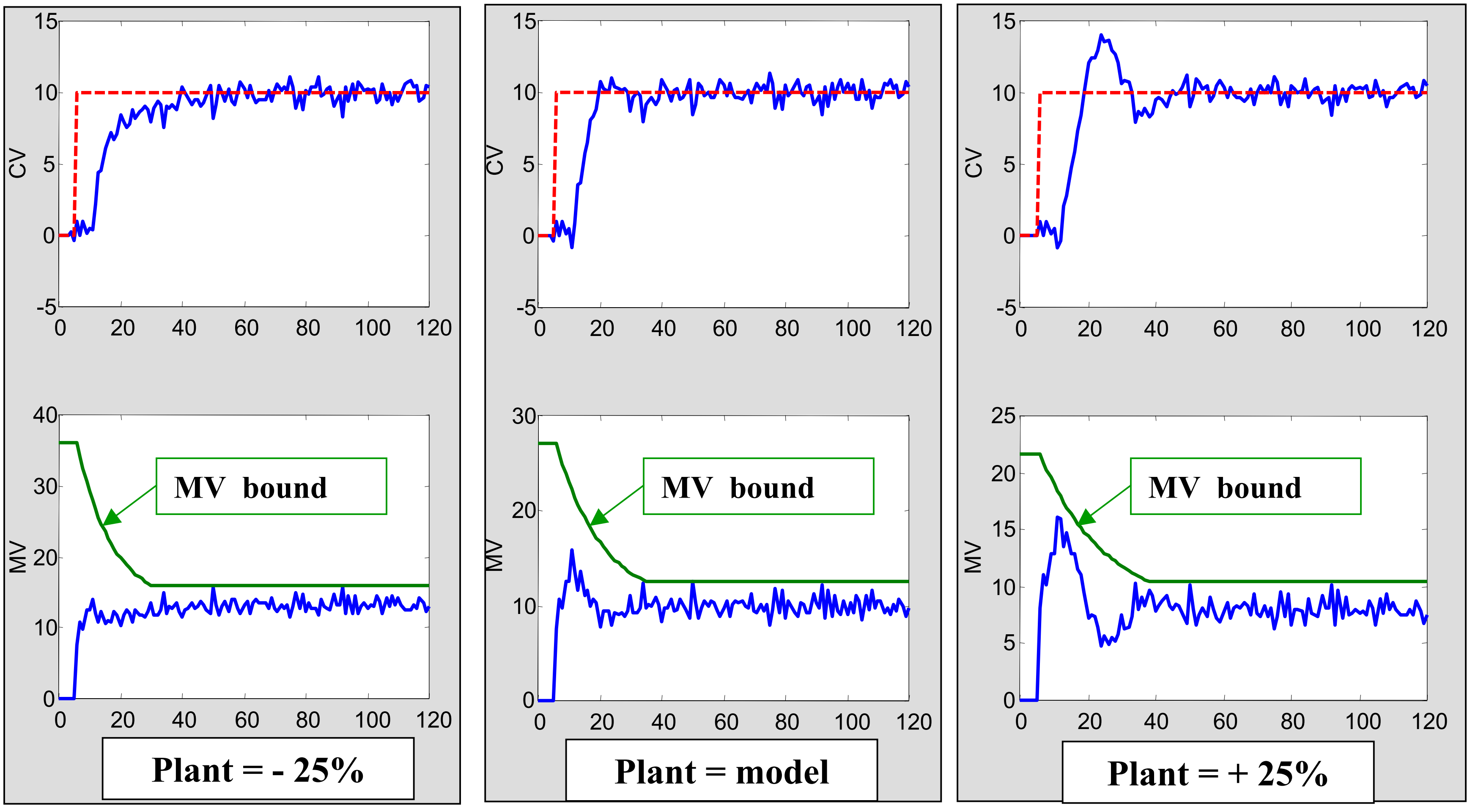
$Td = 0.90$

Apply, is the performance good?



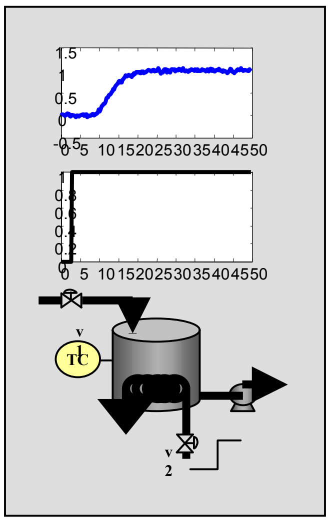
CHAPTER 9: PID TUNING

The tuning is not the best for any individual case, but it is the best for the range of possible dynamics - it is robust!



CHAPTER 9: PID TUNING

Process reaction curve



$Kp = 1$

$\theta = 5$

$\tau = 5$

Solve the tuning problem.

Requires a computer program.

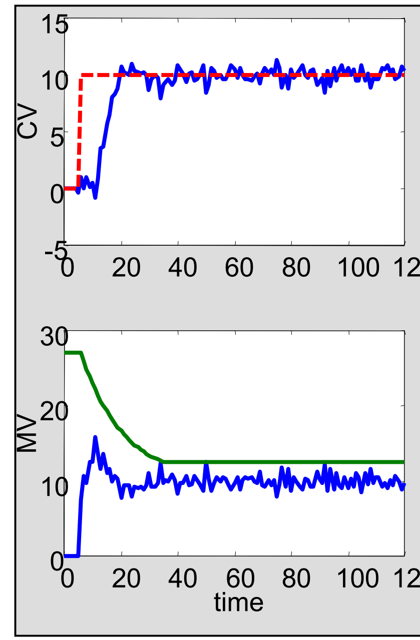
COMBINED DEFINITION OF TUNING

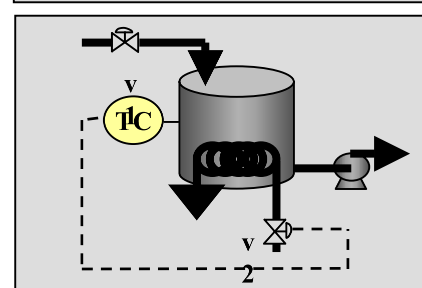
- First order with dead time process model
- Noisy measurement signal
- ± 25% parameters errors between model/plant
- PID controller: determine K_c, T_I, T_d
- Minimize IAE with MV inside bound

$Kc = 0.74$

$TI = 7.5$

$Td = 0.90$





CHAPTER 9: PID TUNING

We could solve each problem individually, but this would be too time consuming. We would like to develop a correlation based on many solutions.

$$\frac{CV(s)}{MV(s)} = \frac{K_c K_p \left(1 + \dfrac{1}{s'(T_I/(\theta+\tau))} + s'(T_d/(\theta+\tau))\right)\left(\dfrac{e^{-s'\theta/(\theta+\tau)}}{1 + s'(\tau/(\theta+\tau))}\right)}{1 + \boxed{K_c K_p}\left(1 + \dfrac{1}{s'\boxed{(T_I/(\theta+\tau))}} + s'\boxed{(T_d/(\theta+\tau))}\right)\left(\dfrac{e^{-s'\theta/(\theta+\tau)}}{1 + s'(\tau/(\theta+\tau))}\right)}$$

Dimensionless Tuning Constants

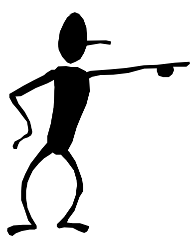
Independent variable

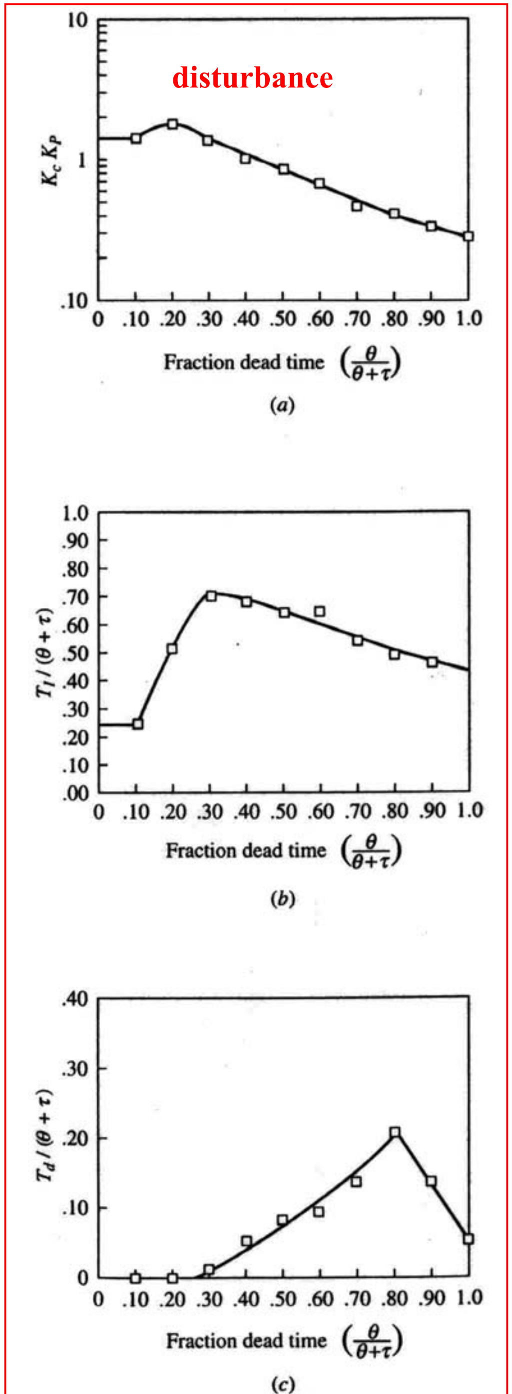
Recall that [τ/(θ+ τ)] + [θ /(θ+ τ)] = 1

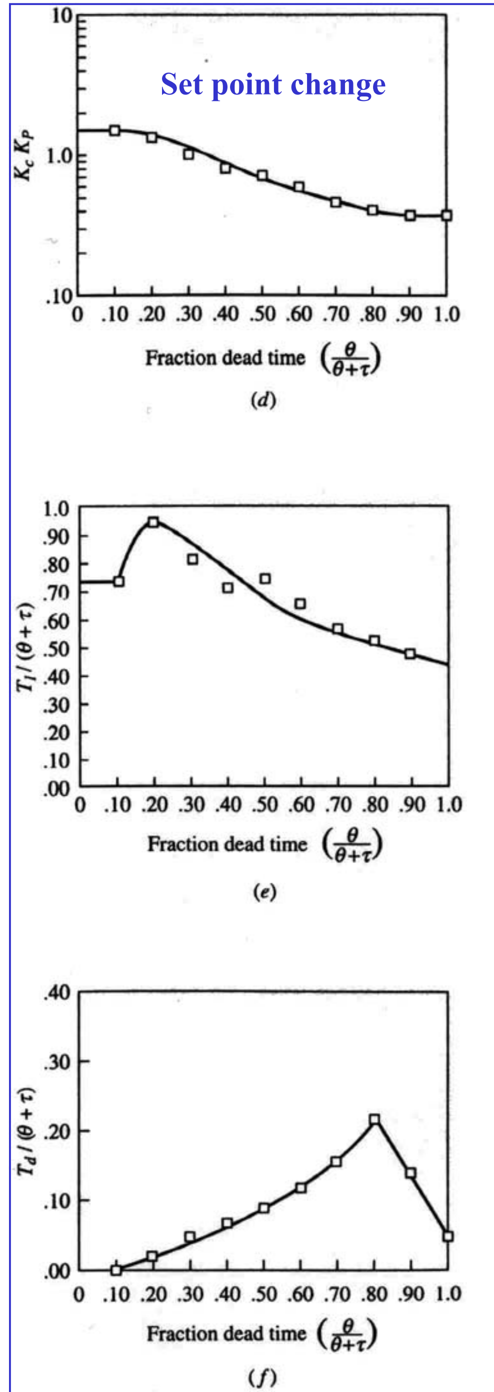
CHAPTER 9: PID TUNING

Tuning Charts for PID Feedback Controllers

These were developed by summarizing a large number of case studies in these dimensionless charts?





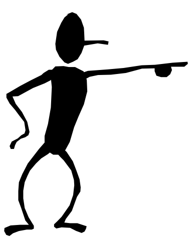


(See page 281 in the textbook for larger plot.)

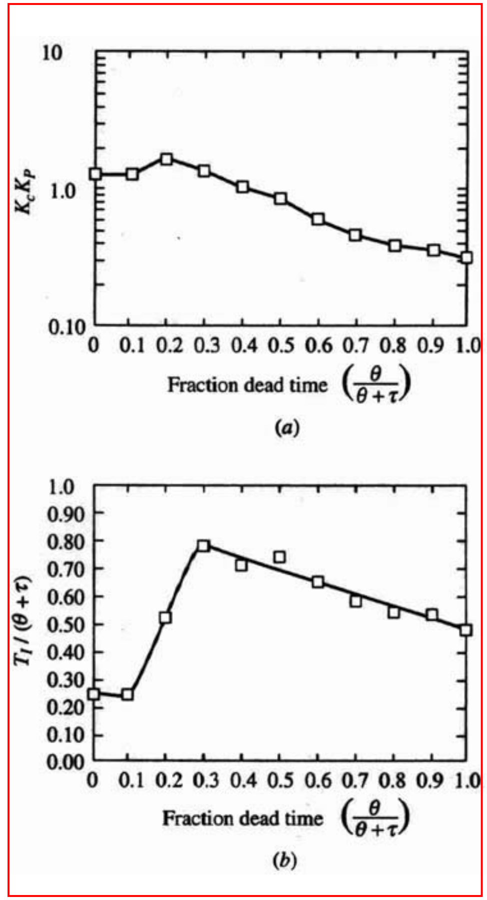
CHAPTER 9: PID TUNING

Tuning Charts for PI Feedback Controllers

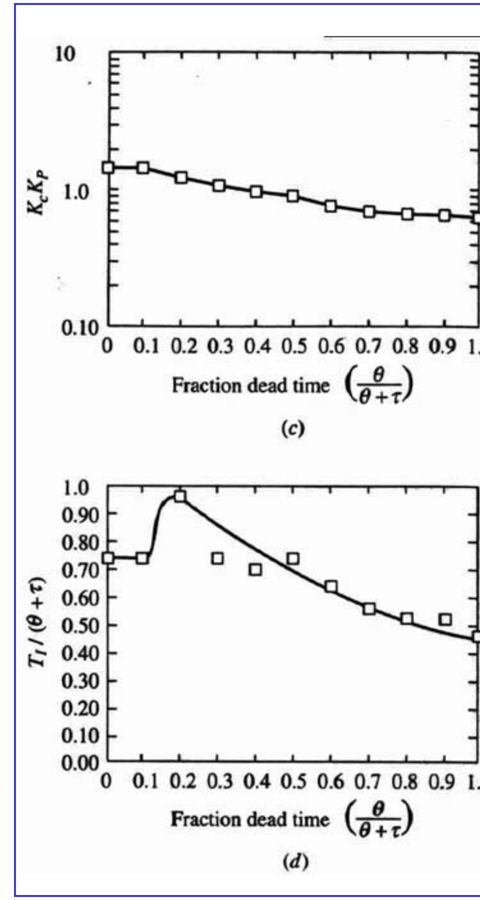
These were developed by summarizing a large number of case studies in these dimensionless charts?



disturbance



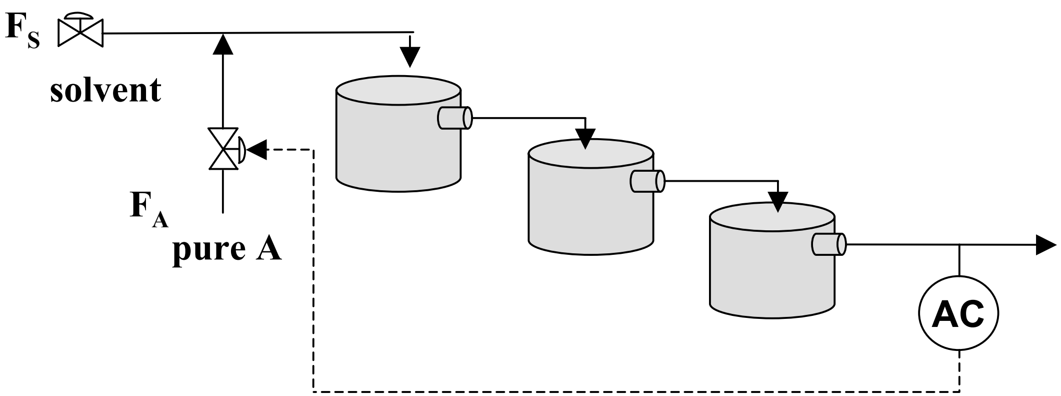
Set point



(See page 286 in the textbook for larger plot.)

CHAPTER 9: PID TUNING

Let's apply the tuning charts to the three-tank mixing process, which is not first order with dead time.



Process reaction curve

Kp = 0.039 %A/%open

θ = 5.5 min

τ = 10.5 min

Tuning from chart

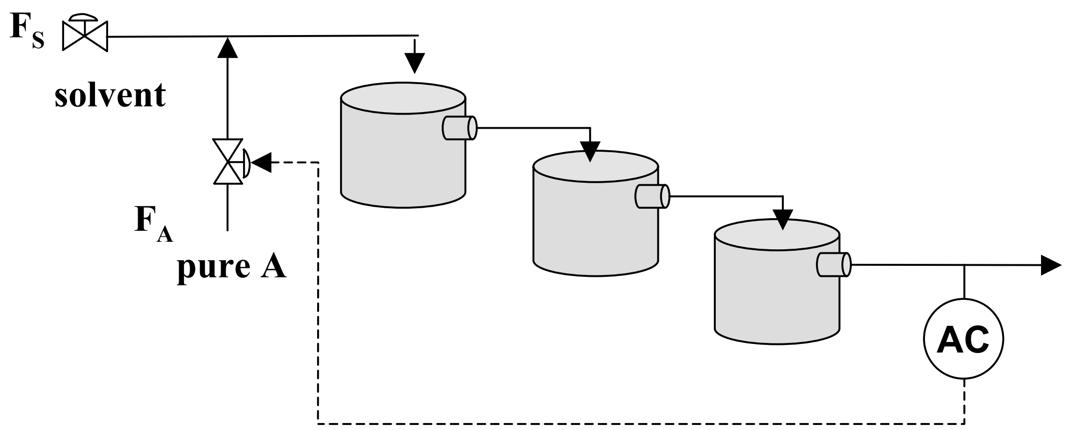
Kc = ??

TI = ??

Td = ??

CHAPTER 9: PID TUNING

Let's apply the tuning charts to the three-tank mixing process, which is not first order with dead time.



Process reaction curve

Kp = 0.039 %A/%open

θ = 5.5 min

τ = 10.5 min

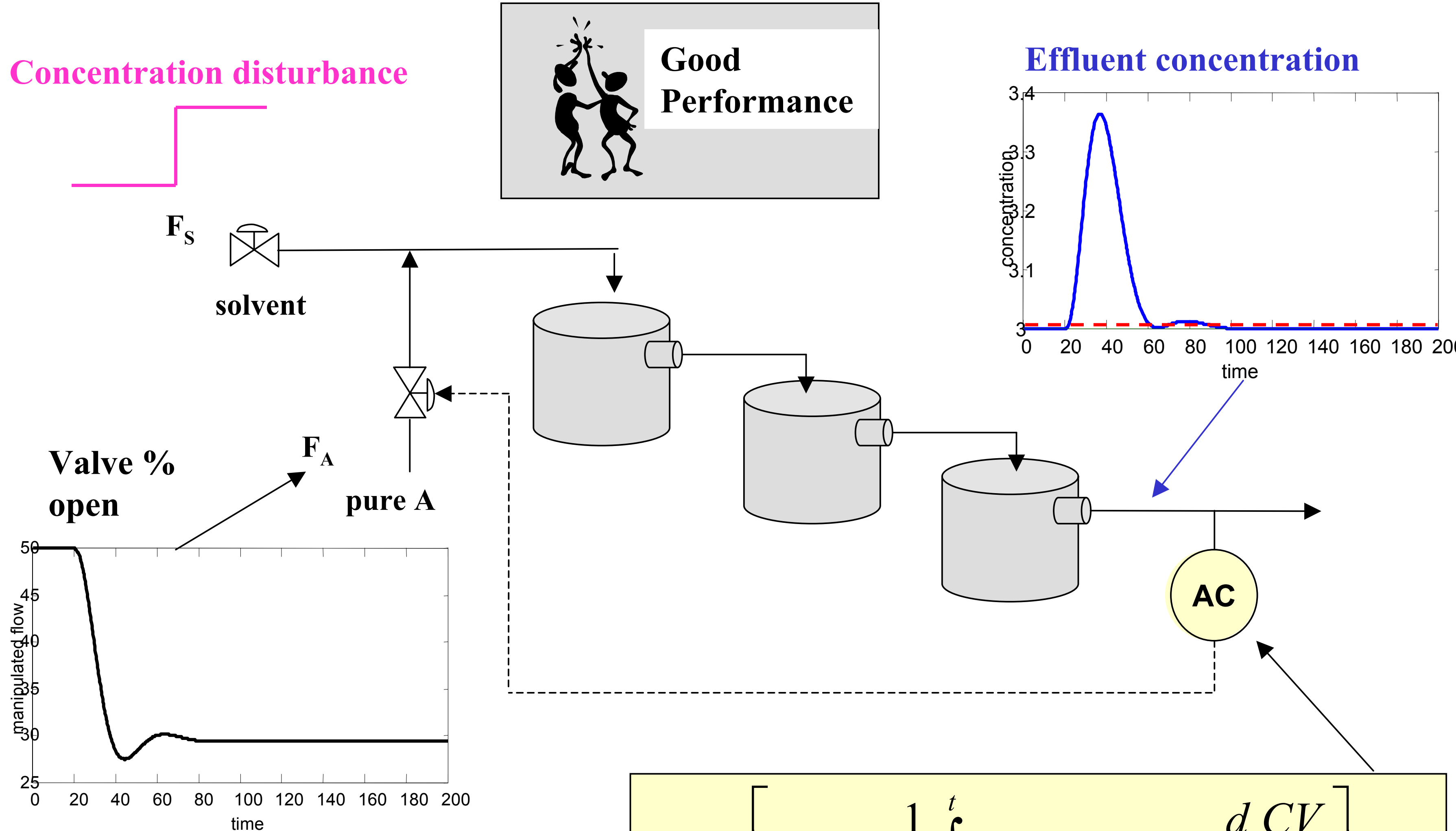
Tuning from chart

Kc = 1.2/0.039 = 30 %open/%A

TI = 0.69(16) = 11 min

Td = 0.05(16) = 0.80 min

CHAPTER 9: PID TUNING



$$v = 30\left[E(t) + \frac{1}{11}\int_0^t E(t')dt' - 0.80\frac{d\,CV}{dt}\right] + 50$$

CHAPTER 9: PID TUNING

FINE TUNING: Process reaction curve and tuning charts provide a good method for tuning many (not all) PID loops. We need to learn how to fine tune loops to further improve performance based on current loop behavior - WHY?

- **Some loops could have different performance objectives**
- **Some loops could have dynamics different from first order with dead time**
- **Could have been error in the process reaction curve, perhaps a disturbance occurred during the experiment.**
- **Plant dynamics can change due to changes in feed flow rate, reactor conversion, and so forth.**

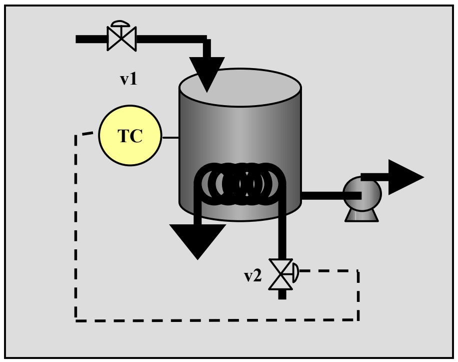
CHAPTER 9: PID TUNING

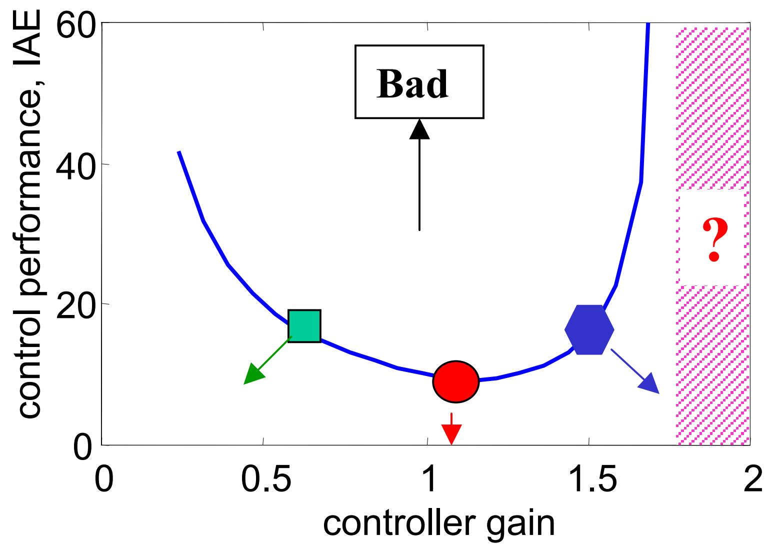
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')dt' - T_d \frac{d\,CV}{dt} \right] + I$$

What is the effect of changing the controller gain on the control performance of a PID loop?

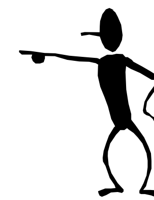
Let's do an experiment by changing Kc and monitoring the performance.

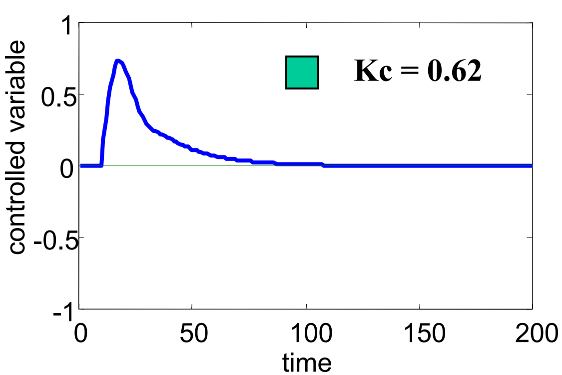
CHAPTER 9: PID TUNING

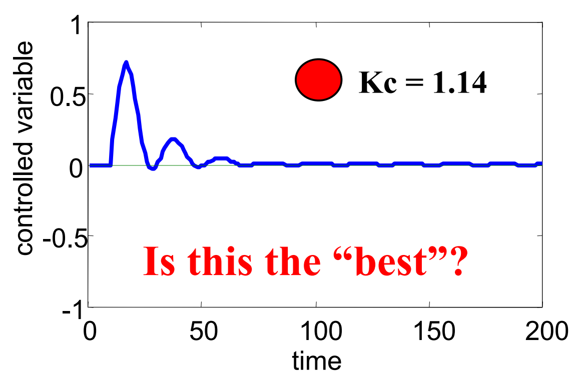


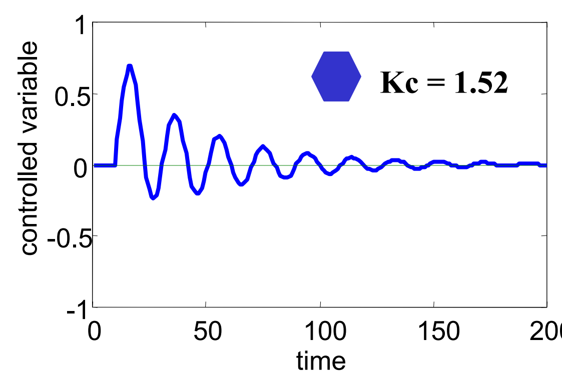


- **Why does IAE increase for small Kc?**
- **Why does IAE increase for large Kc?**









PID controller with Kc changing, TI = 10, Td = 0.

CHAPTER 9: PID TUNING

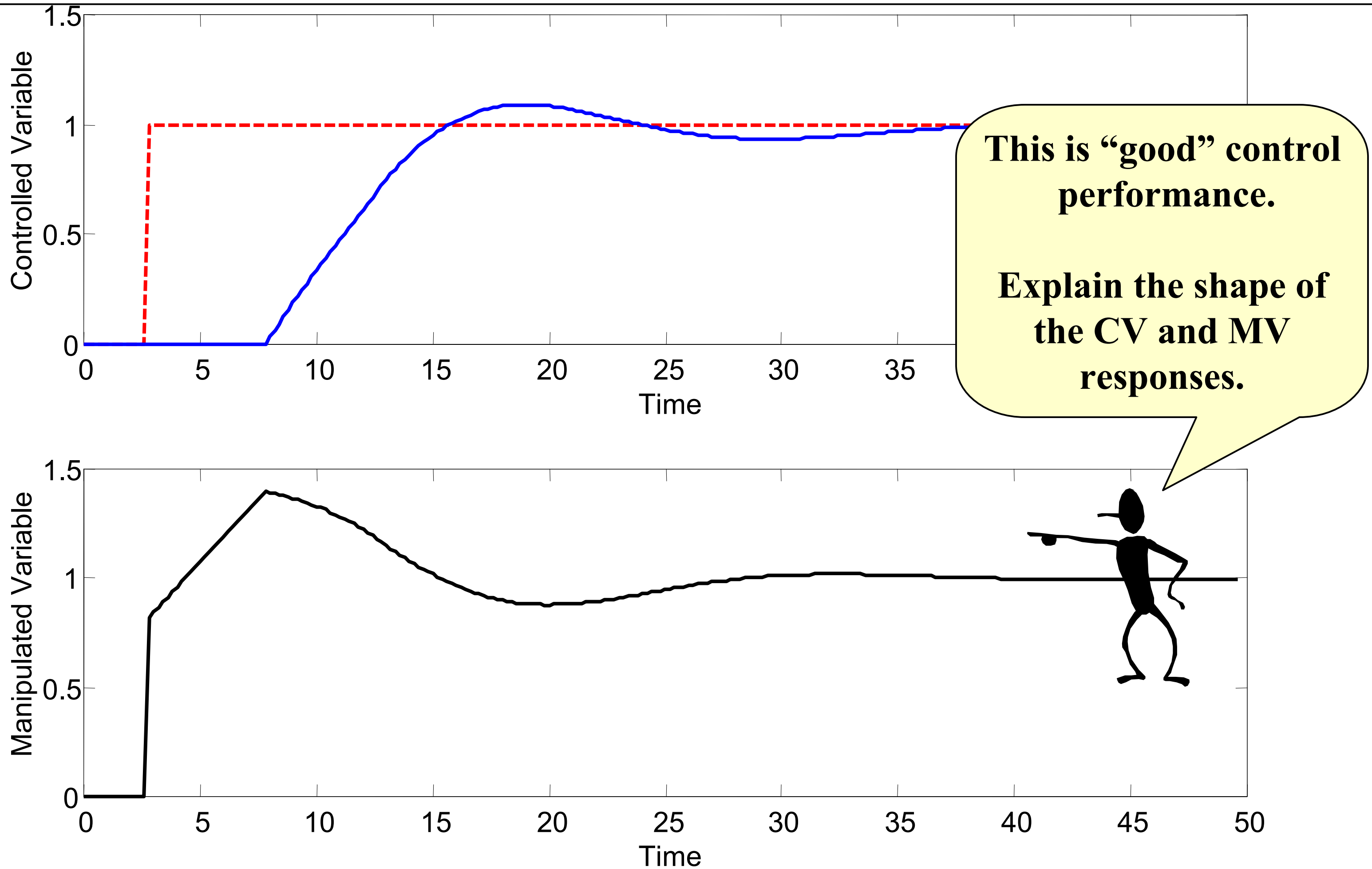
$$MV(t) = K_c \left[E(t) + \frac{1}{T_I} \int_0^t E(t')dt' - T_d \frac{d\,CV}{dt} \right] + I$$

What is the effect of changing the integral time on the control performance of a PID loop?

Is the answer different from Kc? What is different?

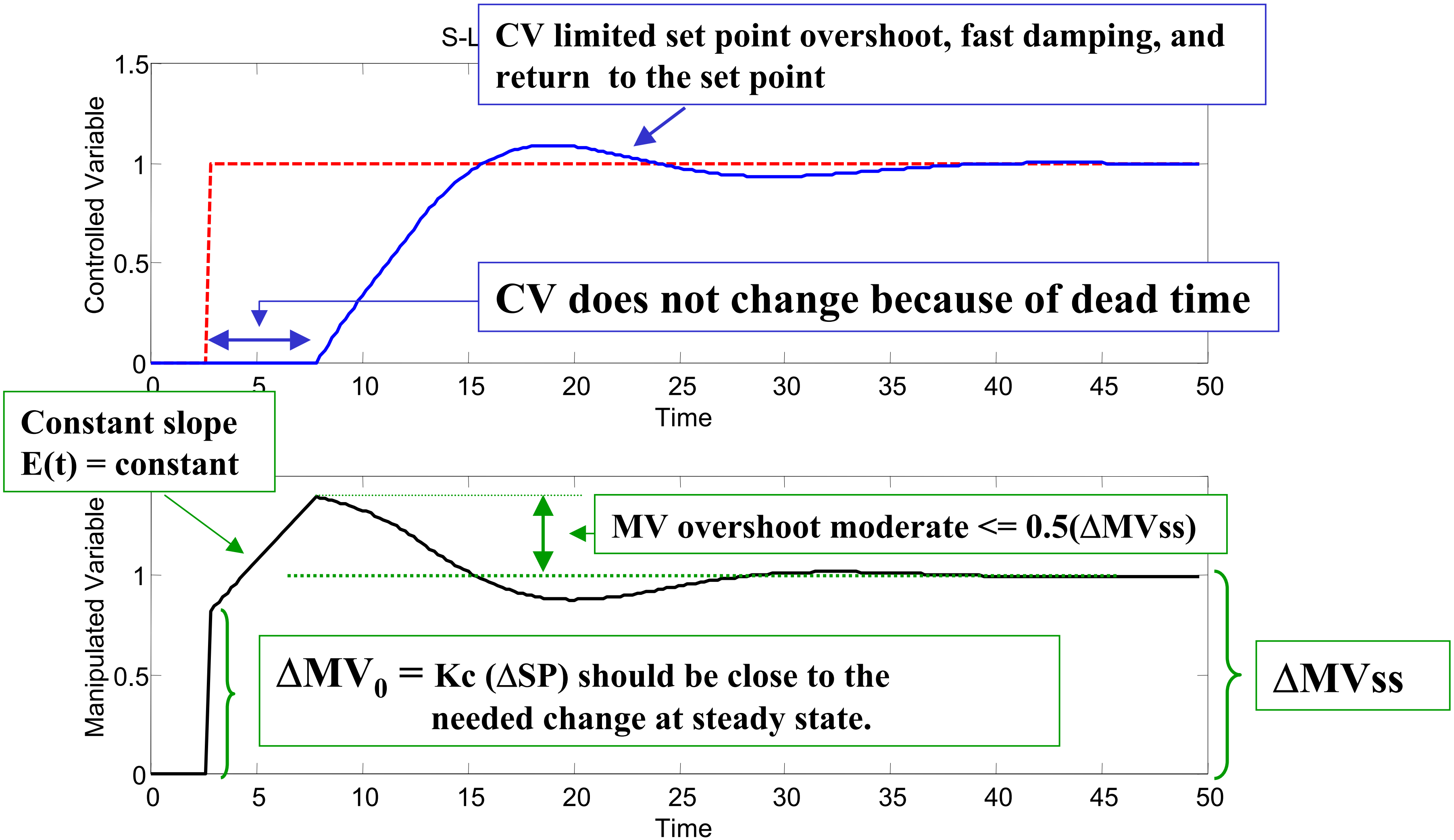
CHAPTER 9: PID TUNING

FINE TUNING: Let's apply our understanding to build fine tuning guidelines.



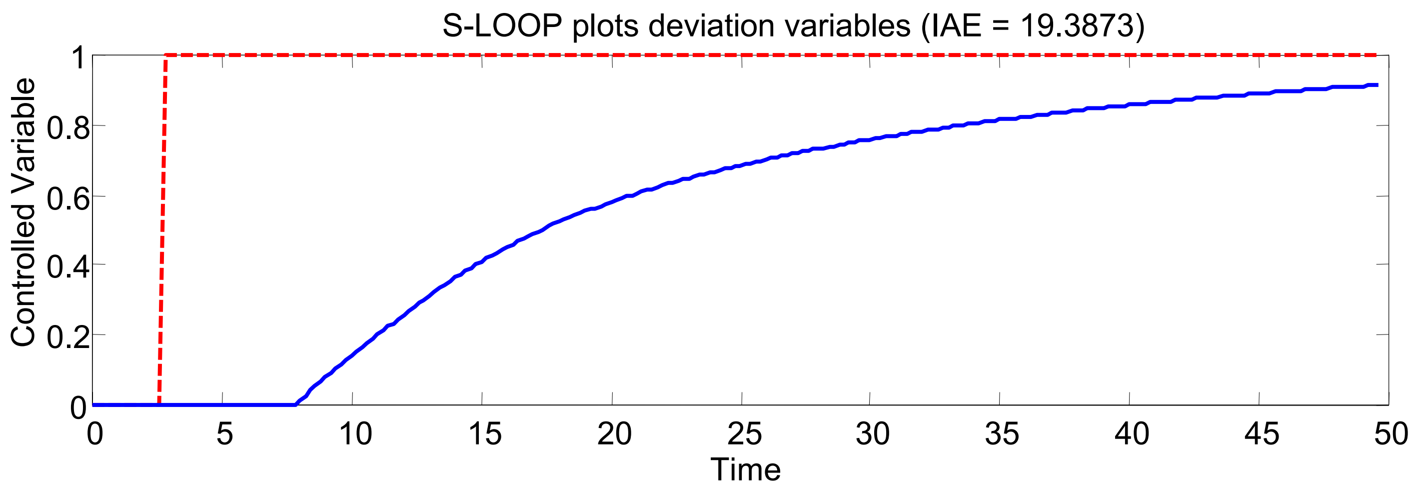
CHAPTER 9: PID TUNING

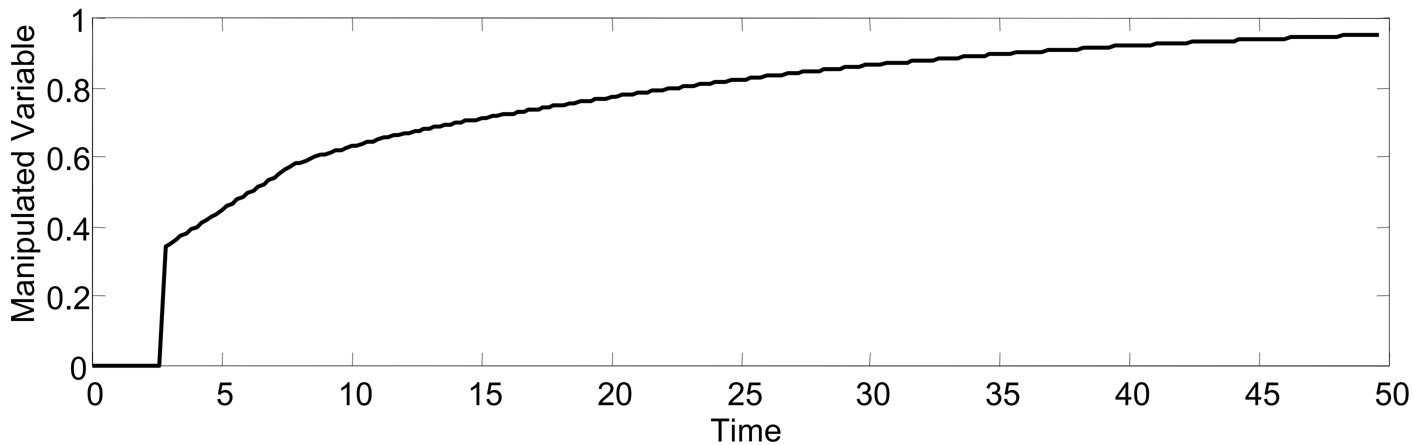
Note: this is a step change to the set point - good for diagnosis!



CHAPTER 9: PID TUNING

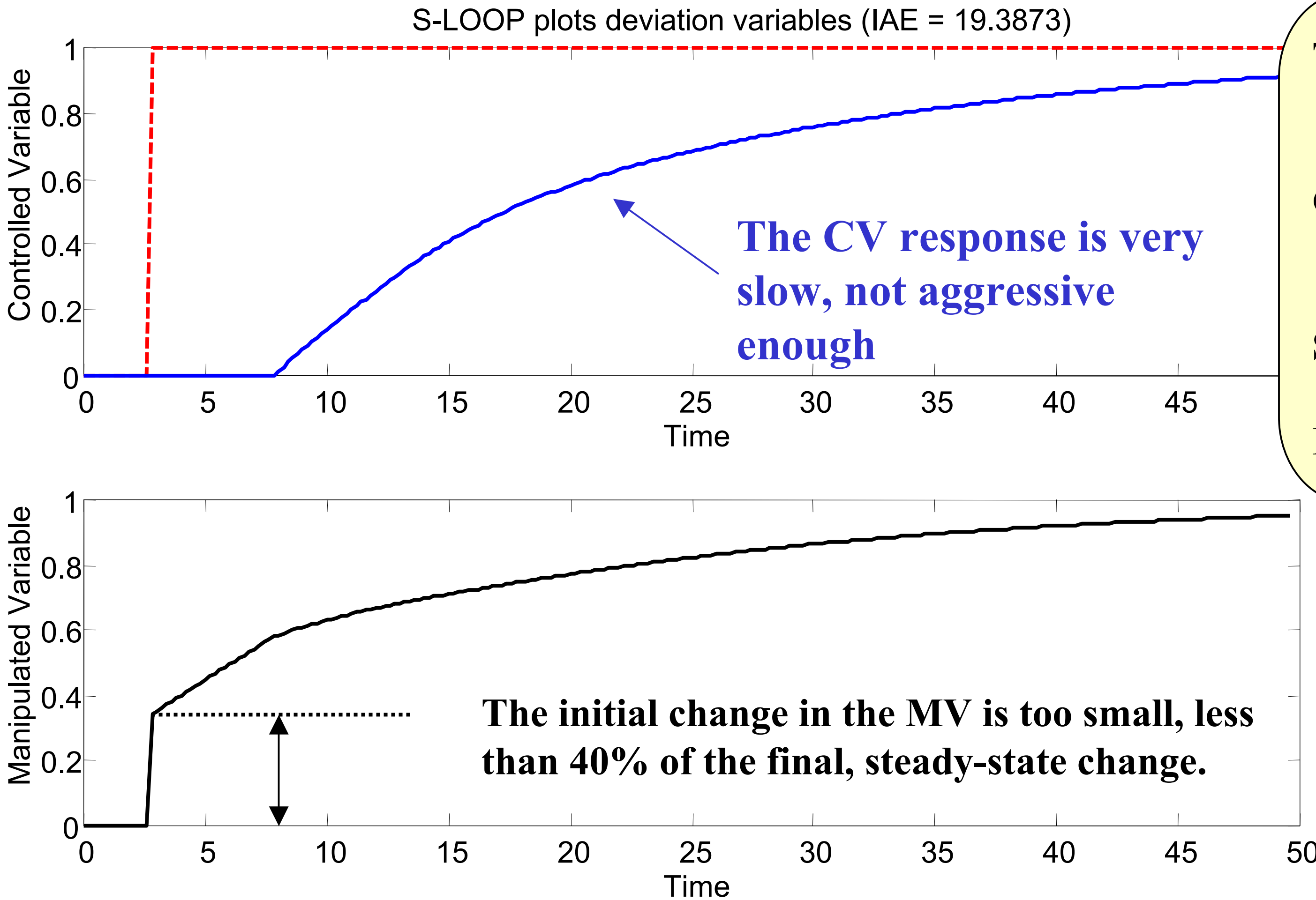
Apply the fine tuning guidelines to the response below and suggest specific changes for improvement.





CHAPTER 9: PID TUNING

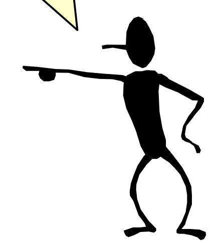
Apply the fine tuning guidelines to the response below and suggest specific changes for improvement.



This is poor control performance.

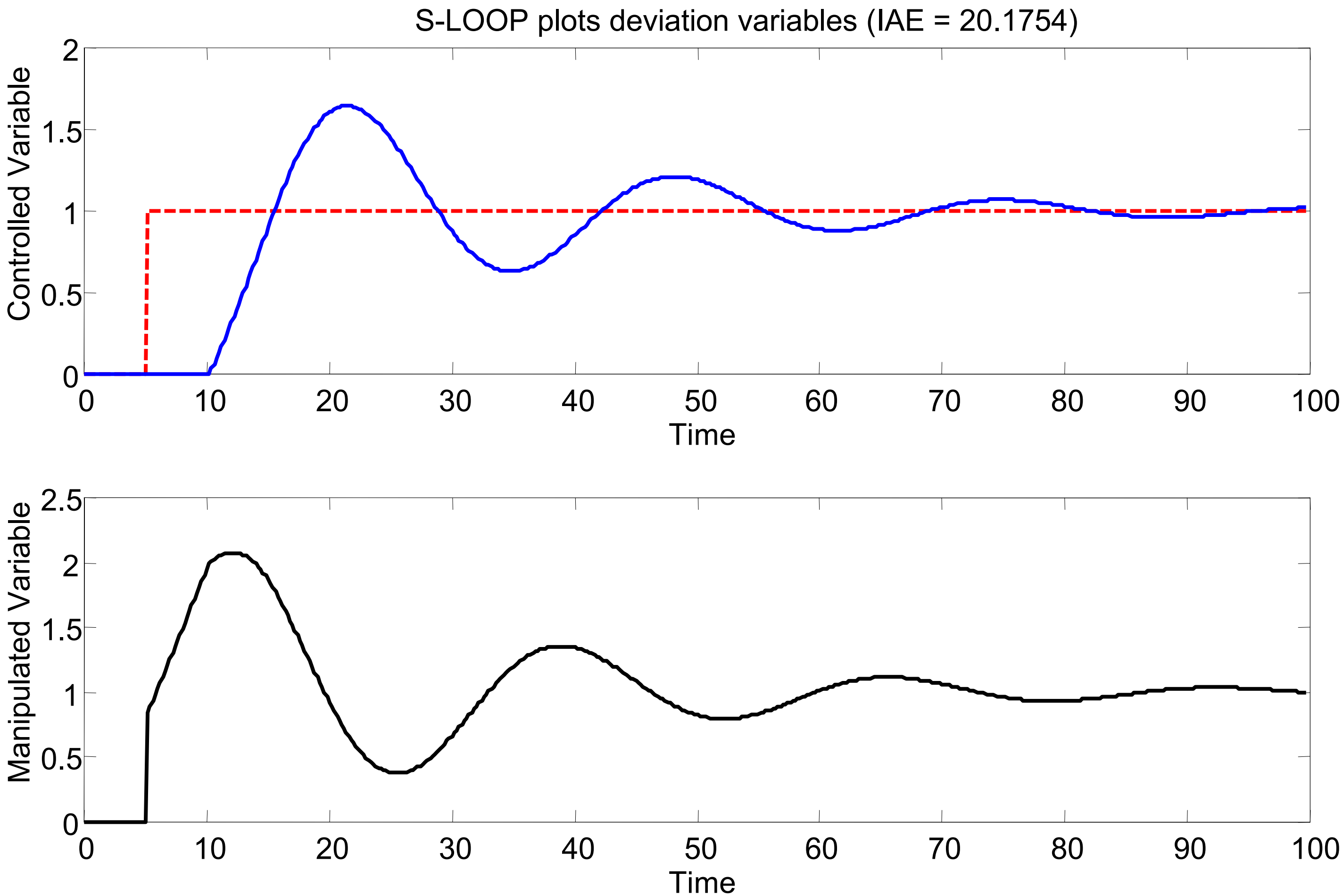
Controller not aggressive enough.

Small ΔMV_0, increase controller gain, K_c by about x2



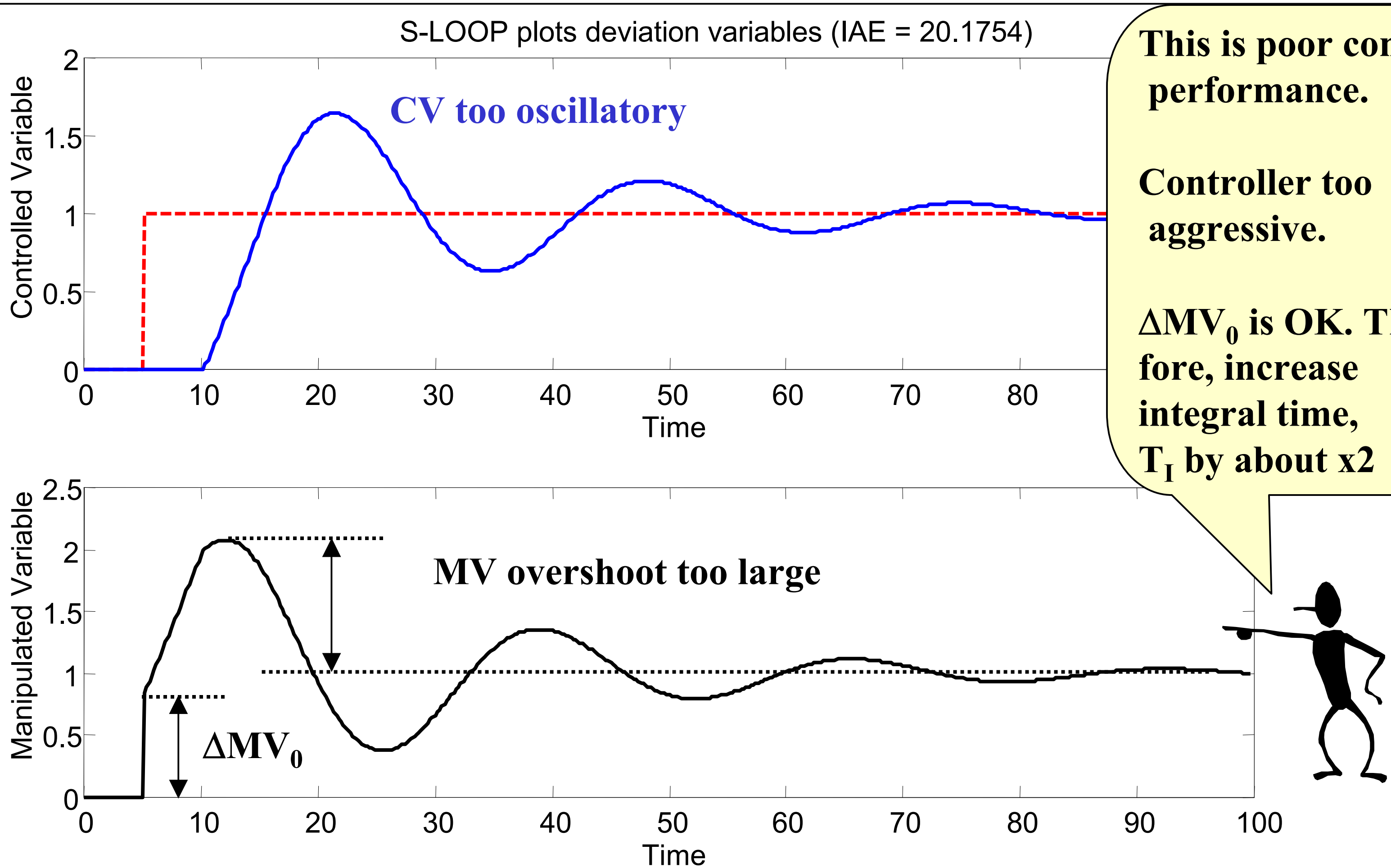
CHAPTER 9: PID TUNING

Apply the guidelines to the response below and suggest specific changes for improvement.



CHAPTER 9: PID TUNING

Apply the guidelines to the response below and suggest specific changes for improvement.



This is poor control performance.

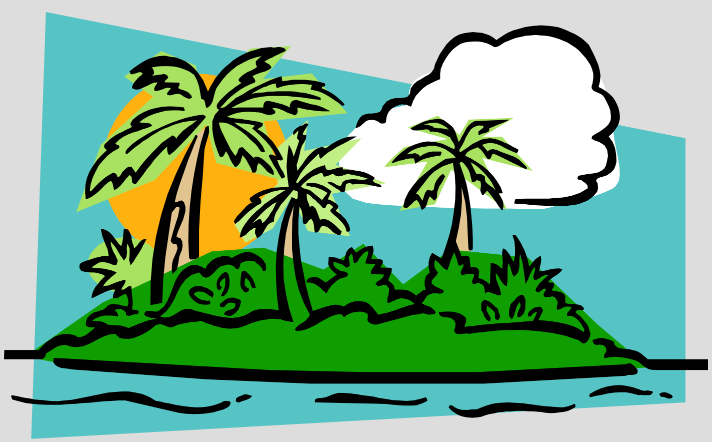
Controller too aggressive.

ΔMV_0 is OK. Therefore, increase integral time, T_I by about x2

CHAPTER 9: PID TUNING, WORKSHOP 1

Imagine that you are shipwrecked on an island and that you do not have your textbook or lecture notes! Naturally, you want to tune some PID controllers.

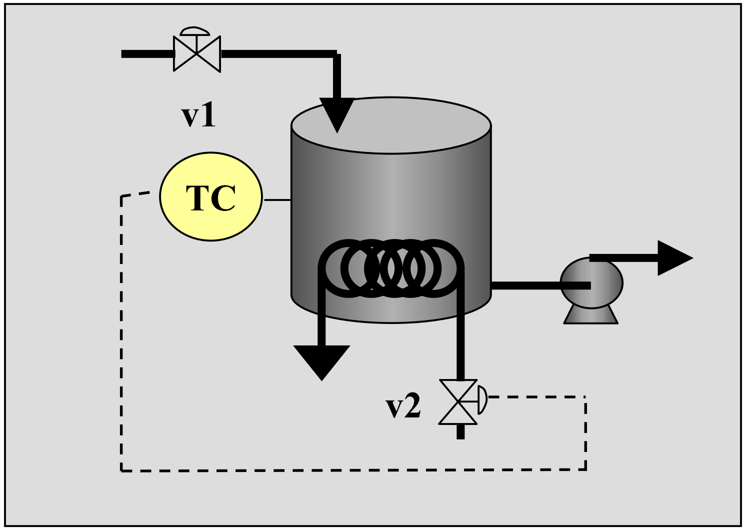
Review the tuning charts and develop some rough guidelines for tuning that you will remember for the rest of your life.



Tropical paradise but no textbook or internet connection.

CHAPTER 9: PID TUNING, WORKSHOP 2

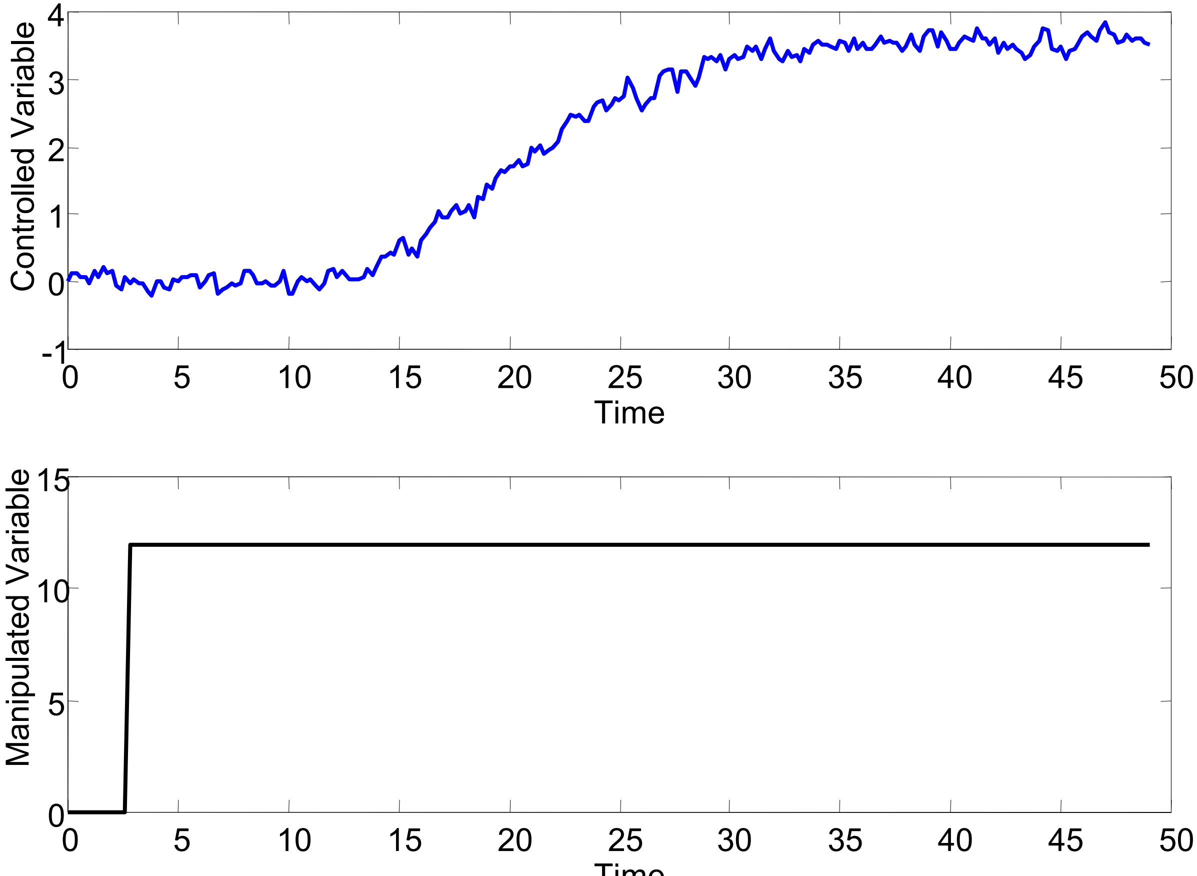
The controller gain has been positive for the examples in the notes. Is K_c always greater than zero? In your answer, discuss the temperature control system in the picture below.

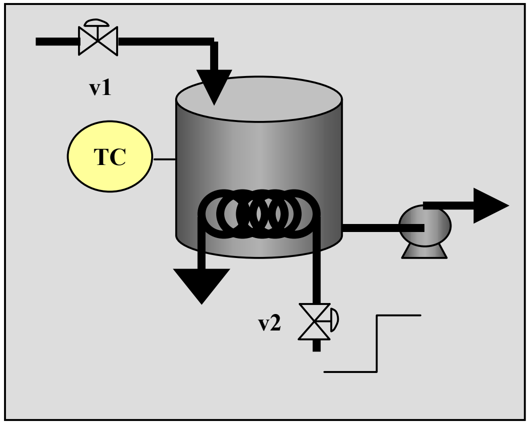


What are the units of the controller gain?

CHAPTER 9: PID TUNING, WORKSHOP 3

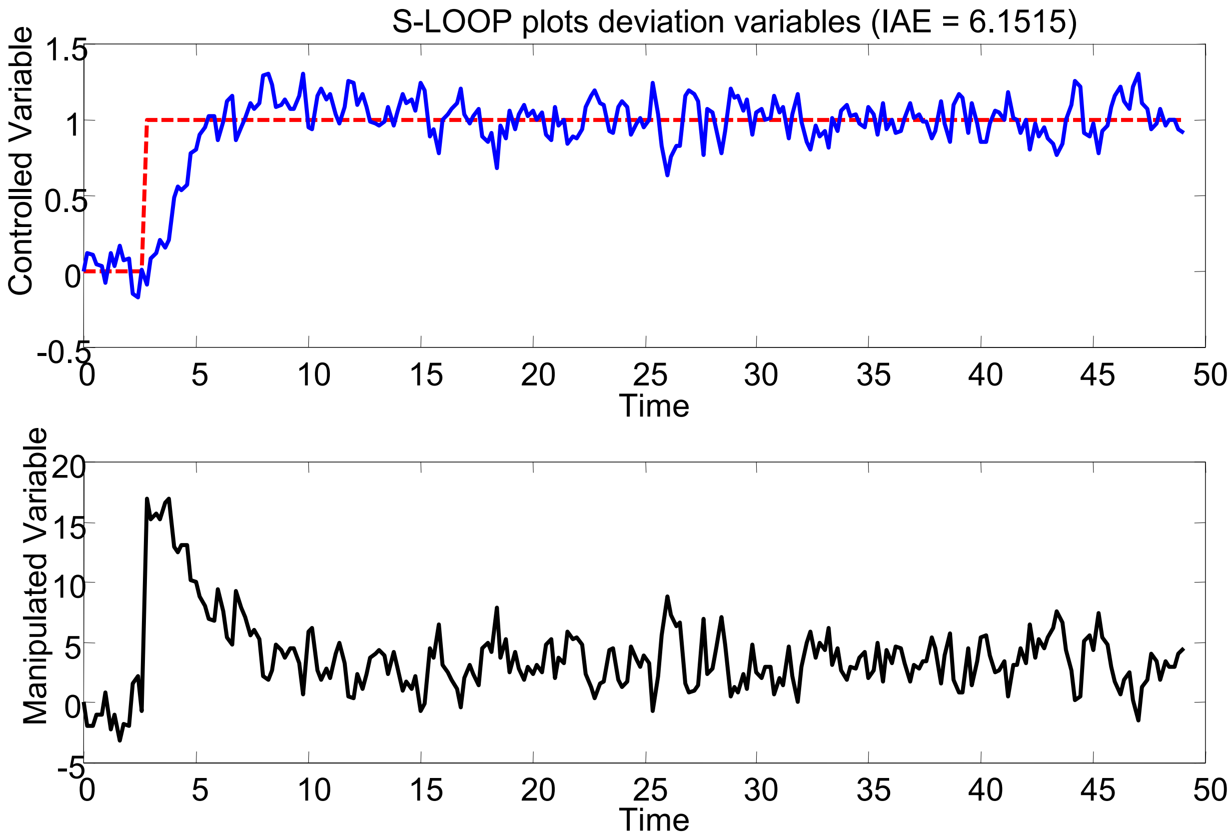
The data below is a <u>process reaction curve</u> for a process, plotted in deviation variables. Determine the tuning for a PID controller.

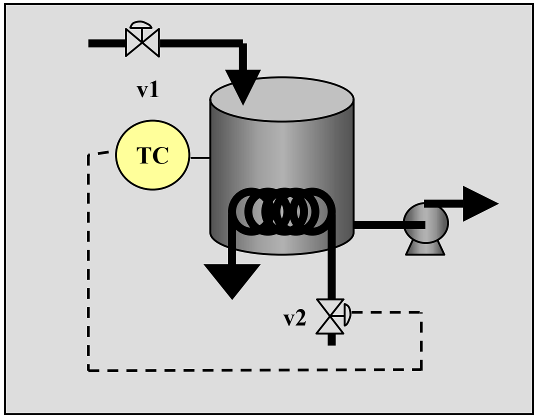




CHAPTER 9: PID TUNING, WORKSHOP 4

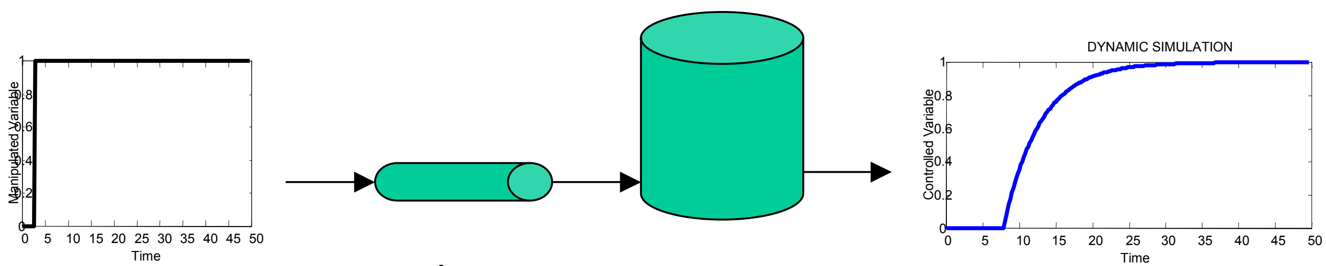
Diagnose the <u>closed-loop data</u> in the figure and suggest modifications, if necessary.





CHAPTER 9: PID TUNING, WORKSHOP 5

Even with the most careful experiments, you are able to determine the model parameters with $\pm$ 50% uncertainty. Recommend initial tuning constant values for a PID controller.



gain

1.0 - 3.0

Dead time

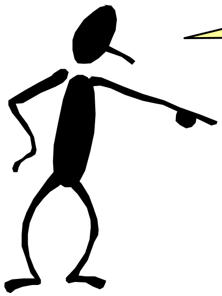
2.5 - 7.5

$$G_P(s) = \frac{CV(s)}{MV(s)} = \frac{2.0 e^{-5s}}{10\,\mathbf{s} + \mathbf{1}}$$

Time constant

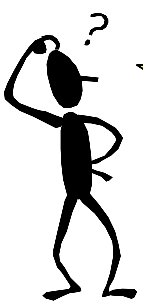
5.0 -1 5.0

CHAPTER 9: PID TUNING



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

- **Explain the performance goals that we seek to achieve via tuning.**
- **Apply a tuning procedure using the process reaction curve and tuning correlations.**
- **Further improve performance by fine tuning**



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 9: LEARNING RESOURCES

- **<u>SITE PC-EDUCATION WEB</u>**
  - Instrumentation Notes
  - Interactive Learning Module (Chapter 9)
  - Tutorials (Chapter 9)

- **Search the WEB and find a "automatic PID tuning" software product. Prepare a critical review of the technique.**

CHAPTER 9: SUGGESTIONS FOR SELF-STUDY

1. **Find some process reaction curve plots in Chapters 3-5 and determine the tuning for PID and PI controllers using the tuning charts.**

2. **Using S_LOOP, repeat the simulation results for the three-tank mixer under PID control. Then determine the sensitivity to changes in tuning by changing K_C and T_I (one at a time, % changes from the basis case tuning); -50%, -10%, +50%. Discuss your results.**

3. **Using S_LOOP, add noise to the measurement in submenu 1, Kn = 0.05 . Simulate with the original tuning and other values for Td. What happens to the performance?**

CHAPTER 9: SUGGESTIONS FOR SELF-STUDY

4. **Formulate questions similar to those in the Interactive Learning Modules, one each for Check Your Reading, Study Questions and Thought Questions.**

5. **In chapters 3-5, find examples of processes for which the tuning from the tuning charts would be (1) applicable and (2) not applicable.**

6. **On Monday, we tuned the three-tank mixer composition controller. On Friday, we anticipate reducing the feed flow rate by 50% (from 7 to 3.5 m^3/min). When this occurs, should we change the tuning of the controller? If yes, which constants and by how much?**

   (Hint: Three-tank mixer model is in Example 7.2 on Page 223 of textbook.)