

## Class 4 Dynamic Process Behavior

## Understanding Dynamic Process Behavior

- To learn about the dynamic behavior of a process, analyze measured process variable test data
- Process variable test data can be generated by suddenly changing the controller output signal
- Be sure to move the controller output far enough and fast enough so that the dynamic behavior of the process is clearly revealed as the process responds
- The dynamic behavior of a process is different as operating level changes (nonlinear behavior) so collect process data at normal operating levels (design level of operation)

## Modeling Dynamic Process Behavior

- The best way to understand process data is through modeling
- Modeling means fitting a first order plus dead time (FOPDT) dynamic process model to the data set:

$$\tau_p \frac{dy(t)}{dt} + y(t) = K_p u(t - \theta_p)$$

where:

$y(t)$  is the measured process variable

$u(t)$  is the controller output signal

- The FOPDT model is low order and linear so it can only approximate the behavior of real processes

## Modeling Dynamic Process Behavior

- When a first order plus dead time (FOPDT) model is fit to dynamic process data

$$\tau_p \frac{dy(t)}{dt} + y(t) = K_p u(t - \theta_p)$$

- The important parameters that result are:
  - Steady State Process Gain,  $K_p$
  - Overall Process Time Constant,  $\tau_p$
  - Apparent Dead Time,  $\theta_p$

**PID Tuning Guide**

Steps to fit a first order plus dead time (FOPDT) dynamic model to process data. "Tuning" is defined to include all dynamic information from the effect of input of the controller through the measured response of the process variable.

Process gain data by fitting the measured response variable with a change in the controller output signal. For accurate results the process must be at steady state, the first derivative must be the zero signal that steady state value.

The data reference sample rate should be less than one per time constant or faster (1/10  $\tau_p$ ).

The controller output should be the measured process variable to cause a shift from the mean level.

The Change Time is the FOPDT dynamic model to the process data set. A FOPDT model has the form:

$$y(t) = K_p \left( \frac{1}{\tau_p s + 1} \right) e^{-\theta_p s} u(t)$$

where:

- $y(t)$  = measured process variable signal
- $u(t)$  = controller output signal
- $K_p$  = process gain, units of  $y/x$
- $\tau_p$  = process time constant, units of time
- $\theta_p$  = process dead time, units of time
- $\theta_p$  = controller gain, units of  $y/x$
- $\tau_p$  = controller time constant, units of time
- $\theta_p$  = controller dead time, units of time
- $\theta_p$  = controller filter constant, units of time

Values of  $K_p$ ,  $\tau_p$ , and  $\theta_p$  that describe the dynamic behavior of your process are important because:

- they are used to calculate the initial controller tuning values ( $K_c$ ,  $\tau_c$ ,  $\theta_c$ ) and  $\theta_c$ .
- the sign of  $K_c$  indicates the action of the controller (+ $K_c$  = reverse acting, - $K_c$  = direct acting).
- the size of  $\tau_c$  indicates the maximum desirable loop sample time (be sure  $T \leq 0.1 \tau_c$ ).
- the size of  $\theta_c$  indicates whether a Smith predictor would be useful (useful when  $\theta_p / \tau_p \geq 0.7$ ).
- the model is used to select the controller, tune the controller, and select the controller parameters.

Then controller is tuned using the following. First, select the controller action. Then, select the controller gain, rate of change, and integral action.

Knowledge of the dynamics of the process, degree of measurement, grade of prediction, and input on other process.

**Initial Controller Tuning**

Desired Tuning:  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$ ,  $\theta_c = 0.1 \theta_p$

Controller Tuning:  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$ ,  $\theta_c = 0.1 \theta_p$

**PID Tuning**

**PI** (Reverse Acting):  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$

**PID Ideal**:  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$ ,  $\theta_c = 0.1 \theta_p$

**PID Ideal with Filter**:  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$ ,  $\theta_c = 0.1 \theta_p$

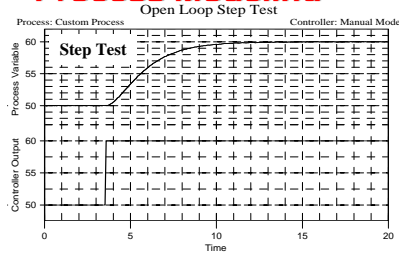
**PID Ideal with Filter and Derivative**:  $K_c = 1.25 \frac{K_p}{\tau_p}$ ,  $\tau_c = 0.5 \tau_p$ ,  $\theta_c = 0.1 \theta_p$

- Tuning of controller means selecting the parameters for "best" operation
- FOPDT model of dynamics of the process are used
  - $K_p$
  - $\tau_p$
  - $\theta_p$
- See correlations
- This "Tuning Guide" is located in the back of the pdf file for the Practical Process Control book
- This is a place to start (close but not best)

## The FOPDT Model is All Important

- model parameters ( $K_p$ ,  $\tau_p$  and  $\theta_p$ ) are used in correlations to compute initial controller tuning values
- sign of  $K_p$  indicates the action of the controller (+ $K_p$  → reverse acting; - $K_p$  → direct acting)
- size of  $\tau_p$  indicates the maximum desirable loop sample time (be sure sample time  $T \leq 0.1 \tau_p$ )

## Step Test Data and Dynamic Process Modeling



- Process starts at steady state
- Controller output signal is stepped to new value
- Measured process variable allowed to complete response

## Process Gain From Step Test Data

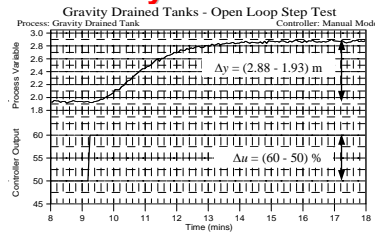
- $K_p$  describes how much the measured process variable,  $y(t)$ , changes in response to changes in the controller output,  $u(t)$
- A step test starts and ends at steady state, so  $K_p$  can be computed from plot axes

$$K_p = \frac{\text{Steady State Change in the Measured Process Variable, } \Delta y(t)}{\text{Steady State Change in the Controller Output, } \Delta u(t)}$$

where  $\Delta u(t)$  and  $\Delta y(t)$  represent the total change from initial to final steady state

- A large process gain means the process will show a big response to each control action

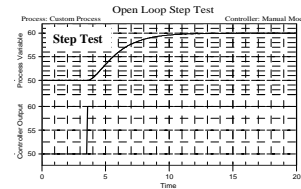
## $K_p$ for Gravity Drained Tanks



$$K_p = \frac{\Delta y}{\Delta u} = \frac{2.88 - 1.93 \text{ m}}{60 - 50 \%} = 0.095 \frac{\text{m}}{\%}$$

Steady state process gain has a:  
size (0.095), sign (+0.095), and units (m/%)

## Overall Time Constant From Step Test Data



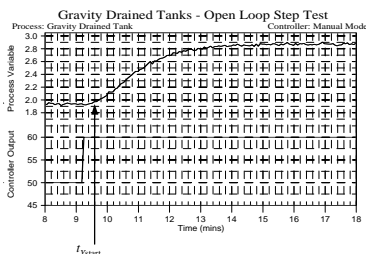
Time Constant  $\tau_p$  describes how fast the measured process variable,  $y(t)$ , responds to changes in the controller output,  $u(t)$

$\tau_p$  is how long it takes for the process variable to reach 63.2% of its total change, starting from when the response first begins

## $\tau_p$ for Gravity Drained Tanks

- 1) Locate where the measured process variable first shows a clear initial response to the step change – call this time  $t_{y\text{start}}$

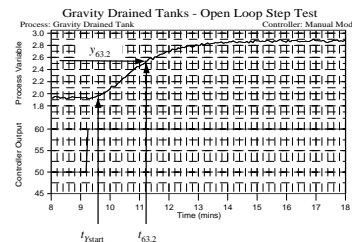
From plot,  $t_{y\text{start}} = 9.6 \text{ min}$



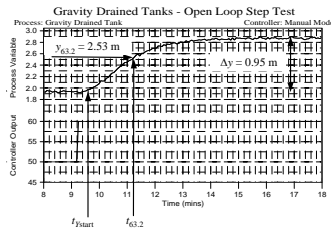
## $\tau_p$ for Gravity Drained Tanks

- 2) Locate where the measured process variable reaches  $y_{63.2}$ , or where  $y(t)$  reaches 63.2% of its total final change

Label time  $t_{63.2}$  as the point in time where  $y_{63.2}$  occurs



## $\tau_p$ for Gravity Drained Tanks

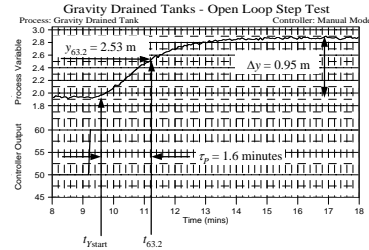


- $y(t)$  starts at 1.93 m and shows a total change  $\Delta y = 0.95 \text{ m}$
- $y_{63.2} = 1.93 \text{ m} + 0.632(\Delta y)$   
 $= 1.93 \text{ m} + 0.632(0.95 \text{ m}) = 2.53 \text{ m}$
- $y(t)$  passes through 2.53 m at  $t_{63.2} = 11.2 \text{ min}$

## $\tau_p$ for Gravity Drained Tanks

- The time constant is the time difference between  $t_{\text{start}}$  and  $t_{63.2}$
- Time constant must be positive and have units of time

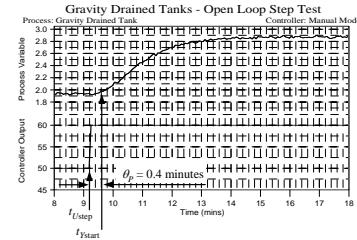
From the plot:  $\tau_p = t_{63.2} - t_{\text{start}} = 11.2 \text{ min} - 9.6 \text{ min} = 1.6 \text{ min}$



## Apparent Dead Time From Step Test Data

- $\theta_p$  is the time from when the controller output step is made until when the measured process variable first responds
- Apparent dead time,  $\theta_p$ , is the sum of these effects:
  - transportation lag, or the time it takes for material to travel from one point to another
  - sample or instrument lag, or the time it takes to collect analyze or process a measured variable sample
  - higher order processes naturally appear slow to respond
- Notes:
  - Dead time must be positive and have units of time
  - Tight control is increasingly difficult as  $\theta_p > 0.7 \tau_p$
  - For important loops, work to avoid unnecessary dead time

## $\theta_p$ for Gravity Drained Tanks



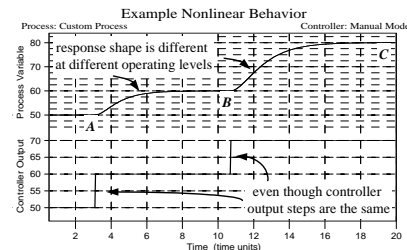
$$\begin{aligned}\theta_p &= t_{\text{start}} - t_{\text{step}} \\ &= 9.6 \text{ min} - 9.2 \text{ min} \\ &= 0.4 \text{ min}\end{aligned}$$

## Processes Have Time-Varying Behaviors

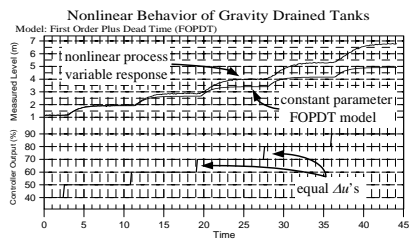
- The predictions of a FOPDT model are constant over time
- But real processes change every day because
  - surfaces foul or corrode
  - mechanical elements like seals or bearings wear
  - feedstock quality varies and catalyst activity drifts
  - environmental conditions like heat and humidity change
- So the values of  $K_p$ ,  $\tau_p$ ,  $\theta_p$  that best describe the dynamic behavior of a process today may not be best tomorrow
- As a result, controller performance will degrade with time and periodic retuning may be required

## Processes Have Nonlinear Behaviors

- The predictions of a FOPDT model are constant as operating level changes
- The response of a real process varies with operating level



## Gravity Drained Tanks is Nonlinear



*A controller should be designed for  
a specific level of operation!*