Tuning Methods of PID Controller

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Session Outlines & Objectives

Outlines

- Tuning methods of PID controller:
  - Ziegler-Nichols Open-loop
  - Coon-Cohen Open-loop
  - Ziegler-Nichols Closed-loop
  - Lambda Tuning
  - Visual Loop Tuning
  - Autotuning

Objectives

- Know the meaning of controller tuning
- Be able to use several PID tuning methods and choose the right tuning methods for specific process control application

Introduction (1)

Controller tuning

- A systematic-adjusting procedure of the controller parameters to obtain a desired performance of the control system

PID control tuning

- It is a matter of selecting the right mix of P, I, and D action to achieve a desired performance

Introduction (2)

Performance criteria for closed-loop systems

- Stable
- Minimal effect of disturbance
- Rapid, smooth response to set point change
- No offset
- No excessive control action
- Robust to plant-model mismatch

Trade-offs in control problems

- Set point tracking vs. disturbance rejection
- Robustness vs. performance

Introduction (3)

How do we know when it’s tuned?

- The process didn’t blow up ☺
- The process measurements stay close enough to the setpoint
- Boss says OK, and you can go home
- You buy a new controller which has different PID algorithm

Introduction (4)

The Problem

- We have the knowledge about the effect of each PID modes to closed-loop response
- But, from what values of P, I and D modes we would pick to start to tune?

The Solutions

- If you have tuned the process before, use **slightly different** values of the old PID controller parameter
- If the results are still not satisfy you, use a PID controller tuning method that we will learn just in a moment that is most suit to your process control application. Keep watch on …

Introduction (5)

General Tuning Procedure

- Before tuning, **FAMILIARIZE** with the **OPERATION RISK**
- Get help with experienced operators, explain your work to him and tell him that **NO PERMISSION IS REQUIRED** if their intervention is **NECESSARY** to save the loop if things go wrong

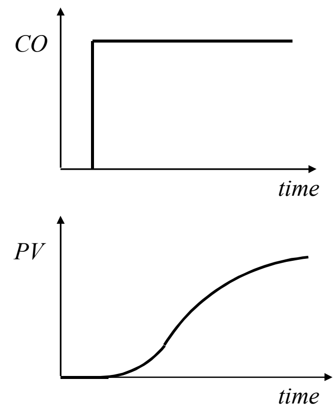
Introduction (6)

Precaution:

All kinds of tuning method should be used for initial setting and fine tuning should be done!!!

Cohen-Coon Open-loop Tuning Method (1)

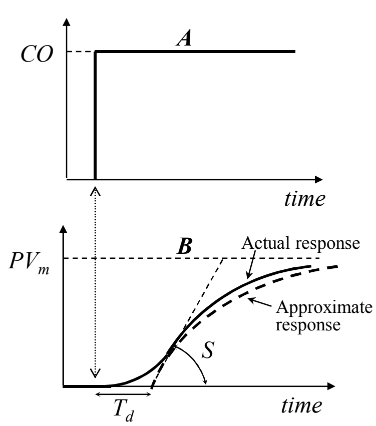
- Proposed in 1953 by G. H. Cohen and G. A. Coon[1]
- Main principles:
  - The process output is affected **not** only by the dynamics of the main process but also by the dynamics of the measuring sensor and final control element
  - They observed that the response of most processing unit to an input change had a **sigmoidal** shape



[1] G. H. Cohen and G. A. Coon, *Theoretical Consideration of Retarded Control*, Trans. ASME,Vol. 75, pp. 827, 1953.

Cohen-Coon Open-loop Tuning Method (2)

- Main principles: (contd.)
  - The sigmoidal shape can be **adequately approximated** by the response of a **first order system with dead time**



$$G_{fpm} = \frac{PV_m}{CO} \simeq \frac{K\,e^{-T_d s}}{\tau s + 1},$$

where

$$K = \frac{B}{A}$$

$$\tau = \frac{B}{S}$$, S is the slope of the sigmoidal response at the point of inflection

T_d = time elapsed until the system responded

Cohen-Coon Open-loop Tuning Method (3)

- Once the value of process parameter are obtained, the PID parameter can be calculated from the following table

Controller	P	I_m	D
P only	$\frac{1}{K}\frac{\tau}{T_d}\left[1+\frac{T_d}{3\tau}\right]$	-	-
PI	$\frac{1}{K}\frac{\tau}{T_d}\left[0.9+\frac{T_d}{12\tau}\right]$	$T_d\frac{30+3T_d/\tau}{9+20T_d/\tau}$	-
PID	$\frac{1}{K}\frac{\tau}{T_d}\left[\frac{4}{3}+\frac{T_d}{4\tau}\right]$	$T_d\frac{32+6T_d/\tau}{13+8T_d/\tau}$	$T_d\frac{4}{11+2T_d/\tau}$

Ziegler-Nichols Open-loop Tuning Method (1)

- Proposed in 1942 by J. G. Ziegler and N. B. Nichols of Taylor Instruments (now part of ABB instrumentation in Rochester, N.Y.) [2]
- It is done in **manual** mode
- It is a way of relating the process parameters (i.e. delay time, process gain and time constant) to the controller parameters (i.e. controller gain and reset time)
- It has been developed for use on **delay-followed-by-first-order-lag** processes

[2] J. G. Ziegler and N. B. Nichols, *Optimum Setting for Automatic Controllers*, Trans. ASME,Vol. 64, pp. 759-768, 1942.

Ziegler-Nichols Open-loop Tuning Method (2)

The Procedure

1. Put the control system in **MANUAL** (without feedback)
2. Adjust the controlled system manually to the desired operating point (start-up control loop)
3. Apply manually a **STEP** change of the controller output (CO) (usually 5 – 10 % or depending of your process gain)
4. Wait until the process variable (PV) is settled at steady-state condition

Ziegler-Nichols Open-loop Tuning Method (3)

5. Determine process parameter (delay time, process gain and time constant) from the graphics

CO

PV

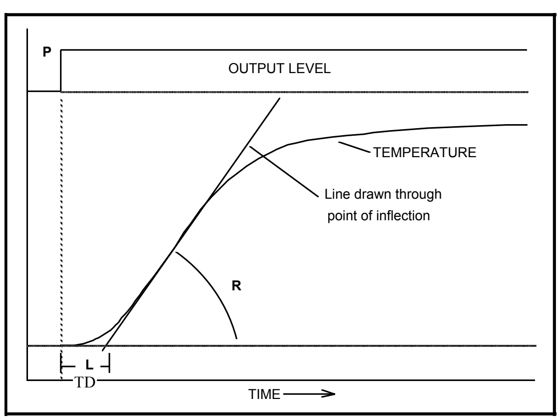


FIGURE 6: PROCESS REACTION CURVE - SIMPLE

Ziegler-Nichols Open-loop Tuning Method (4)

6. Once the value of process parameter are obtained, the PID parameter can be calculated from the following table

Controller	***P***	I_m	***D***
P only	$\frac{1}{K}\left(\frac{\tau}{T_d}\right)$	-	-
PI	$\frac{0.9}{K}\left(\frac{\tau}{T_d}\right)$	$0.33\ T_d$	-
PID	$\frac{1.2}{K}\left(\frac{\tau}{T_d}\right)$	$2\ T_d$	$0.5\ T_d$

Ziegler-Nichols Closed-loop Tuning Method (1)

- Proposed in 1942 by J. G. Ziegler and N. B. Nichols of Taylor Instruments (now part of ABB instrumentation in Rochester, N.Y.)
- Also known as **continuous cycling** or **ultimate gain** methods
- It has been developed for use on **delay-followed-by-first-order-lag** processes
- It has been refined for other specific process control objectives

Ziegler-Nichols Closed-loop Tuning Method (2)

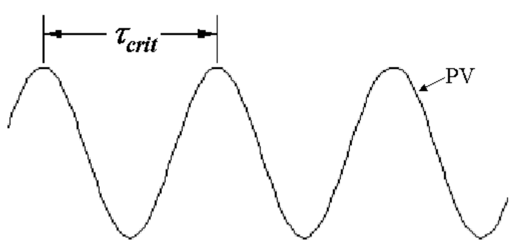
The Procedure

1. At the controller, select proportional-only (**P-ONLY)** control, i.e. set ***P*** to the lowest value (***PB*** to the highest value) and I_m to infinity (I_r to zero) and ***D*** to zero (smallest possible influence of the controller)
2. Adjust the controlled system manually to the desired operating point (start-up control loop)
3. Set the manipulated variable of the controller to the manually adjusted value (reset bias ***b***) and switch to automatic operating mode
4. Continue to gradually increase ***P*** (decrease ***PB***) until the controlled variable encounters harmonic oscillation. If possible, small step changes in the setpoint should be made during the ***P*** adjustment to cause the control loop to oscillate
5. Take down the adjusted ***P*** value as critical proportional-action coefficient P_{crit}

Ziegler-Nichols Closed-loop Tuning Method (3)

The Procedure (contd.)

6. Determine the time span for one full oscillation amplitude as t_{crit}, if necessary by taking the time of several oscillations and calculating their average



Ziegler-Nichols Closed-loop Tuning Method (4)

The Procedure (contd.)

7. Once the value for P_{crit} and τ_{crit} are obtained, the PID parameter can be calculated from the following table

Controller	P	I_m	D
P only	**0.5** P_{crit}	-	-
PI	**0.45** P_{crit}	**0.833** τ_{crit}	-
PID	**0.6** P_{crit}	**0.5** τ_{crit}	**0.125** τ_{crit}

Ziegler-Nichols Closed-loop Tuning Method (5)

Modified Ziegler-Nichols setting

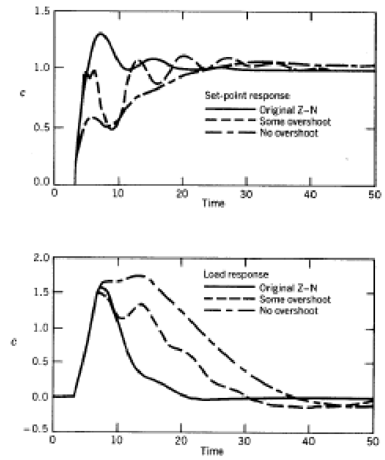
Controller	P	I_m	D
PID original	**0.6** P_{crit}	**0.5** τ_{crit}	**0.125** τ_{crit}
PID some overshoot	**0.33** P_{crit}	**0.5** τ_{crit}	**0.33** τ_{crit}
PID no overshoot	**0.2** P_{crit}	**0.3** τ_{crit}	**0.5** τ_{crit}

Ziegler-Nichols Closed-loop Tuning Method (6)

❑ **Examples**

$$G_p(s) = \frac{4e^{-3.5s}}{7s+1} \left.\right\} \begin{matrix} P_c = 0.95 \\ \tau_c = 12 \end{matrix}$$

Controller	P	I_m	D
PID original	**0.57**	**6.0**	**1.5**
PID some overshoot	**0.31**	**6.0**	**0.4**
PID no overshoot	**0.19**	**6.0**	**4.0**



Ziegler-Nichols Closed-loop Tuning Method (6)

Advantages of continuous cycling method

- ❑ No a priori information on process required
- ❑ Applicable to all stable processes
- ❑ Only a single experimental test is needed
- ❑ It does not require trial and error
- ❑ The controller settings are easily calculated

Ziegler-Nichols Closed-loop Tuning Method (7)

Disadvantages of continuous cycling method

- Time consuming
- Loss of product quality and productivity during the tests
- Continuous cycling may cause the violation of process limitation and safety hazards
- Not applicable to open-loop unstable process
- First-order and second-order process without time delay will not oscillate even with very large controller gain

  → Motivates Relay Feedback Method (Åström and Hagglund, 1984)

Lambda Tuning (1)

- Developed for achieving smooth setpoint response or load change
- Guarantees stability, robustness and no overshoot
- Very popular in pulp & paper industry

Two basic steps of lambda (λ) tuning:

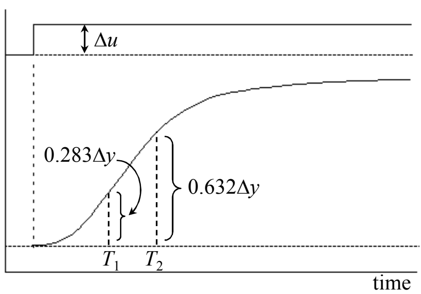
- Process model identification
- Lambda tuning
  - 1st order process with dead time
  - Integrating process (i.e. level control)

Lambda Tuning (2)

1st Order Process with Dead Time

Procedure:

- Manually, bump the *CO* then observe the PV_m



The estimated process parameters:

- Process gain: $G_p = \dfrac{\Delta y}{\Delta u}$
- Process time constant: $\tau_p = 1.5(T_2 - T_1)$
- Process dead time: $T_d = T_2 - \tau_p$

Lambda Tuning (3)

1st Order Process with Dead Time (contd.)

Lambda Tuning:

- Choose the desired closed-loop time constant, λ (typically 2 to 3 times the process constant) ← sluggish response!

PID tuning parameters:

- Proportional gain: $P = \dfrac{2\tau_p + \tau_d}{2G_p(\lambda + \tau_d)}$
- Integral action: $T_m = \tau_p + \dfrac{\tau_d}{2}$
- Derivative action: $D = \dfrac{\tau_p\ \tau_d}{2\ \tau_p + \tau_d}$

Lambda Tuning (4)

Lambda Tuning's Rule of Thumb:

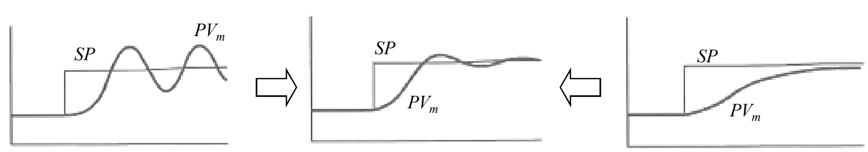
- Integral time should no be smaller than the process time constant
- Level control oscillating? Remove nearly all integral action
- Poll time should be less than one-tenth the process time constant
- Filter time constant should be less than one fifth the process time constant
- Closed-loop time constant is usually greater than the process time constant

Visual Loop Tuning (1)

Problems

- ❑ The loop is unstable (or apparently so)
- ❑ The loop is sluggish in response to upsets or setpoint changes

How to improve the performance of a loop by using **NO** algebra?

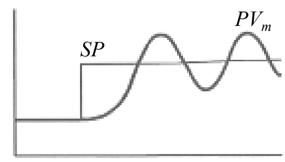


Apparently unstable response | "Good" response? | Sluggish response

Visual Loop Tuning (2)

Apparent Instability

- The loop oscillates
  - Because of excessive feedback, or
  - Of being perturbed periodically by another process



Procedure:

- Put the loop in manual (if it is safe to do so)
- In manual mode, the process appears to settle down → poorly tuned

Tuning problems:

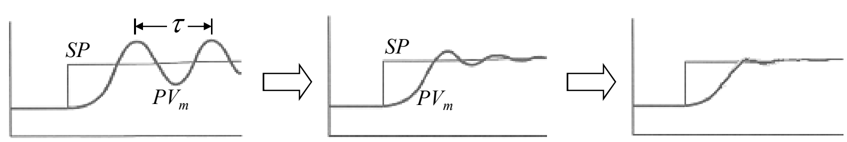
- Is the oscillation caused by too much or too little gain/integral/ derivative or their combinations?

Visual Loop Tuning (3)

Apparent Instability (contd.)

Tuning procedure:

- **Self-regulating Processes**
  - **<u>If</u>** the value of I_m (min/repeat) is **<u>less than half</u>** of the oscillation period τ
    - First, **<u>Increase</u>** the value of I_m
    - If the value of I_m (min/repeat) is **<u>longer than</u>** the oscillation period, it is safe to decrease the gain (P)



Apparently unstable response | Increasing the value of I_m (min/repeat) | Lowering the gain (P)

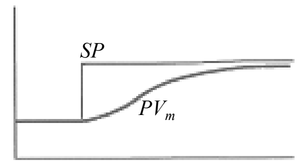
- **Non Self-regulating Processes**
  - Use the longest value of I_m (min/repeat) as much as possible or completely remove the integral action. If the problem persists, then lowering the gain (P)

Visual Loop Tuning (4)

Sluggish Response

Common causes:

- The loop usually has no derivative action
- The value of I_m (min/repeat) is long relative to the process response time
- The value of gain is too low



Visual Loop Tuning (5)

Sluggish Response (contd.)

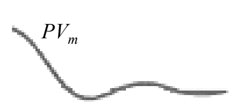
Tuning procedure:

1. Adjusting Gain

- Set the I_m as longest as possible and set D to zero.
- Place the controller in manual mode, then step out the CO at a reasonable value
- Immediately put the controller back in auto mode. Watch the process response to know what the controller action does
- Repeat the process until we get one cycle of process output swinging

Swinging more than one cycle
Too much gain
→ lowering the gain

Swinging less than one cycle
Too little gain
→ increasing the gain



Swinging in one cycle
Reasonable gain achieved

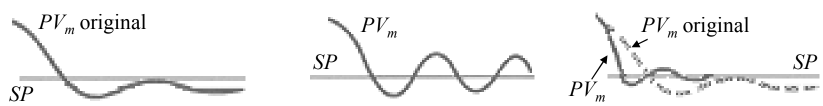
Visual Loop Tuning (6)

Sluggish Response (contd.)

Tuning procedure:

2. Adjusting Integral Action

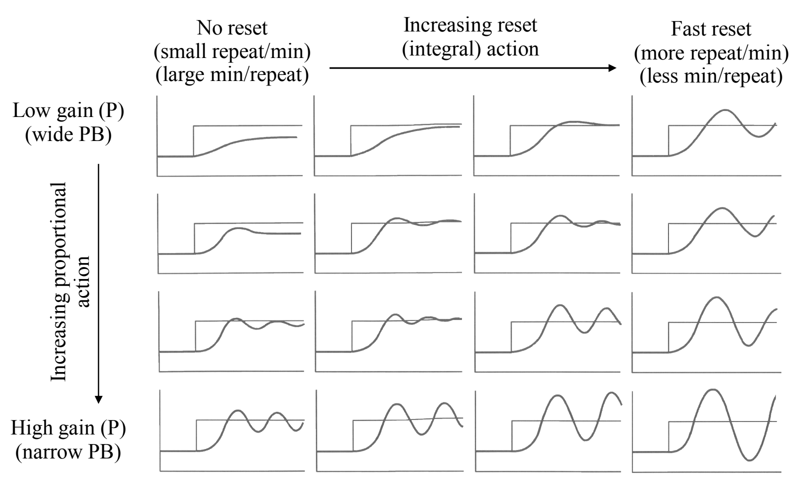
- Place the controller in manual mode, shorten the value of I_m, then step out the CO at a reasonable value
- Immediately put the controller back in auto mode. Watch the process response to know what the controller action does
- Repeat the process until we get the PV_m ramps back to setpoint about **half** as fast as it moved away from setpoint form the CO step



Response with reasonable gain (swinging in one cycle) | To little I_m (swinging at setpoint) | Reasonable I_m

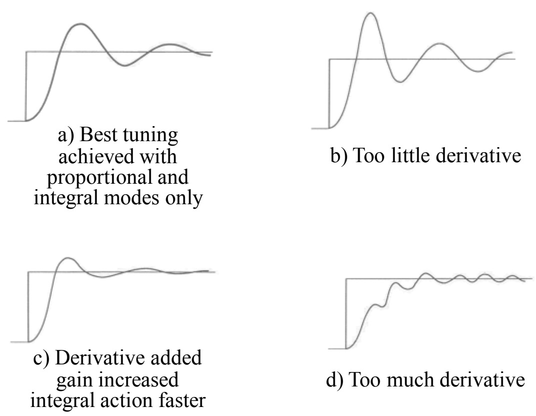
Visual Loop Tuning (7)

Tuning map for gain (*P*) and reset effect (I_m)



Visual Loop Tuning (8)

The Effect of Adding Derivative



What is Autotuning?

- Autotuning (also known as self-tuning) is a feature supplied by many controller, PLC and DCS vendors that allows the controller to “tune itself”
- It minimize the task of a control engineer in manually tuning the loops

Why Autotuning?

- The process is nonlinear or operated under widely varying conditions
  - → Need various combination of tuning parameters for different operating condition ← can be also accomplished by using operator's log
- The process characteristic change rapidly
  - → Frequent manual changing of the tuning parameters can not be expected to be able to produce satisfactory results
- The end user doesn't have the knowledge or experience for successful manual tuning

Autotuning Categories

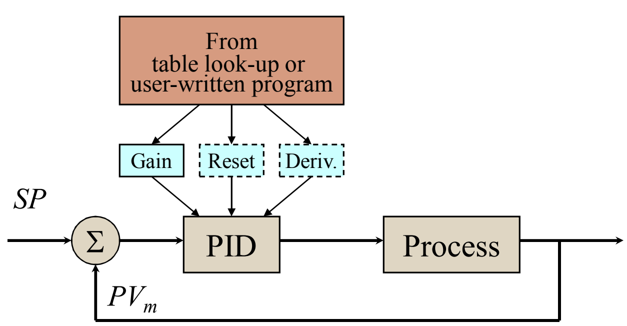
A variety of autotuning techniques found on the market:

- Scheduled tuning
- On-demand tuning
- On-line tuning

Scheduled Tuning (1)

- ❑ Merely, an automation of the "operator's log" concept
  - The users have to provide the correct value either by means of a table look-up or a user-written program
- ❑ Tuning parameters are changed automatically as operating points change
- ❑ No assessing and modifying of the controller performances by determining improved tuning parameters

Scheduled Tuning (2)



Region	Boundaries	Gain	Reset	Deriv.
1	0 – 30%	P_1	I_1	D_1
2	30 – 70%	P_2	I_2	D_2
3	70 – 100%	P_3	I_3	D_3

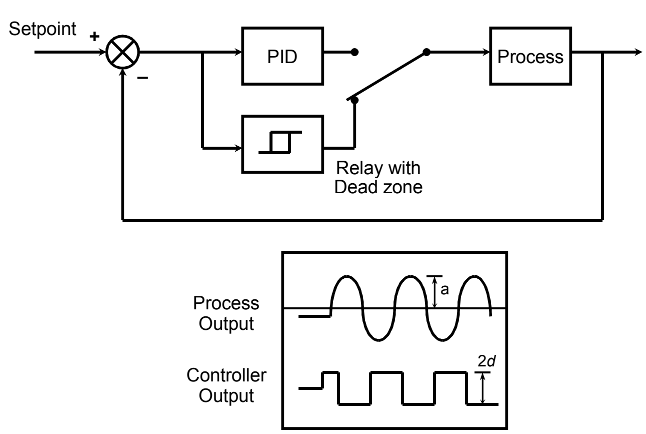
- ❑ Example: Fisher DPR900™ Single-loop Controller

On-demand Tuning (1)

- It is simply an automation of the open- or closed-loop testing method
  - Open-loop tuning methods:
    - Ziegler-Nichols (most common)
    - Lambda tuning
    - ...
  - Closed-loop tuning method:
    - Relay Feedback autotuning ← motivated by Ziegler-Nichols closed-loop tuning method
- User presses a ‘tune’ button to start the tuning procedures which carry out automatically
- The tentative tuning values are display for confirmation. If confirmed, they are inserted into the control algorithm

On-demand Tuning (2)

Relay Feedback Autotuning Method



On-demand Tuning (3)

Relay Feedback Autotuning Method (contd.)

The Procedure

- Forces the system to oscillate by a relay controller
- Require a single closed-loop experiment to find the ultimate frequency information
- No *a priori* information on process is required
- Switch relay feedback controller for tuning
- Find P_{crit} and calculate τ_{crit} according to the formula

$$\boxed{\tau_{crit} = \frac{4\,d}{\pi\,a}}$$

- User specified parameter: *d*
  - Decide "*d*" in order not to perturb the system too much
- Mostly use Ziegler-Nichols tuning rules for PID tuning parameters

On-line Tuning (1)

- The tuning parameters are determined by an auxiliary program that automatically evaluates the closed-loop behavior and calculates and modifies the tuning parameters whenever necessary
- Methods:
  - Pattern recognition
  - Others use a more formal mathematical procedure

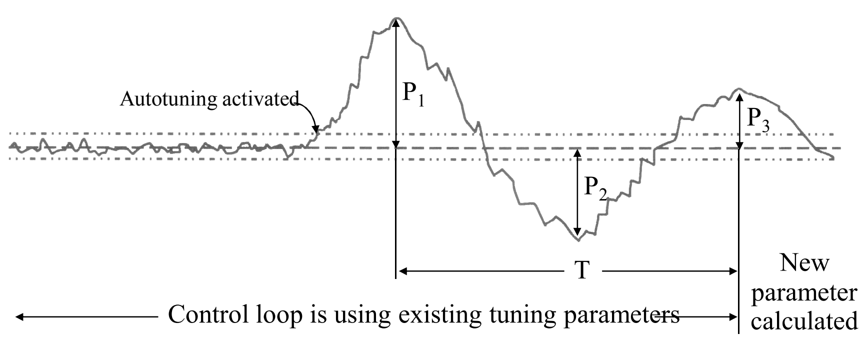
On-line Tuning (2)

Pattern Recognition Approach

- Example: The Foxboro EXACT™ (Expert Adaptive Controller Tuner)
  - It observers the pattern of the response, then invokes a set of rules for determining new tuning parameters that will drive the pattern closer to a desired response pattern
  - The technique:
    - Does not require artificial load upsets – instead it utilizes the normal process disturbances that occur; and
    - Does not attempt to impose an arbitrary mathematical model on the process

On-line Tuning (3)

- The Foxboro EXACT™



Session Summary

- Manual tuning of PID controller can be conducted in various ways by means of some plant test
- There simply is no way to analytically tune a controller if we do not know the type of algorithm and the units
- Autotuning simplifies the tuning procedure of PID controller