APCO Inc.
Advanced Process Control & Optimization

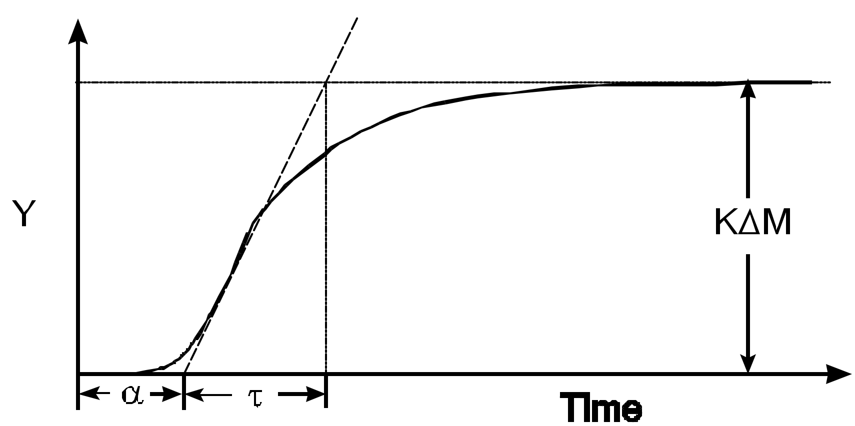
Open Loop Tuning Rules

Based on approximate process models

Process Reaction Curve:

The process reaction curve is an approximate model of the process, assuming the process behaves as a first order plus deadtime system. The process reaction curve is identified by doing an open loop step test of the process and identifying process model parameters.

- Put the controller in manual mode
- Wait until the process value (Y) is stable and not changing
- Step the output of the PID controller - The step must be big enough to see a significant change in the process value. A rule of thumb is the signal to noise ratio should be greater than 5.
- Collect data and plot as shown below.
- Repeat making the step in the opposite direction.
- K = the process gain $K = \frac{Change\_in\_Process\_Value}{Change\_in\_Manipulated\_Value}$



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Open Loop Tuning Rules

Ziegler-Nichols			
Controller Type	K_c	τ_I	τ_D
P	$\frac{1}{K}\left(\frac{t}{a}\right)$	___	___
PI	$\frac{.9}{K}\left(\frac{t}{a}\right)$	$3.33a$	___
PID	$\frac{1.2}{K}\left(\frac{t}{a}\right)$	$2.0a$	$0.5a$
Recommended Range of Applicability 1.0<(α/τ)<0.1			

Cohen-Coon			
Controller Type	K_c	τ_I	τ_D
P	$\frac{1}{K}\left(\frac{t}{a}\right)\left[1+\frac{1}{3}\left(\frac{a}{t}\right)\right]$	___	___
PI	$\frac{1}{K}\left(\frac{t}{a}\right)\left[0.9+\frac{1}{12}\left(\frac{a}{t}\right)\right]$	$a\left[\frac{30+3\left(\frac{a}{t}\right)}{9+20\left(\frac{a}{t}\right)}\right]$	___
PD	$\frac{1}{K}\left(\frac{t}{a}\right)\left[\frac{5}{4}+\frac{1}{6}\left(\frac{a}{t}\right)\right]$	___	$a\left[\frac{6-2\left(\frac{a}{t}\right)}{22+3\left(\frac{a}{t}\right)}\right]$
PID	$\frac{1}{K}\left(\frac{t}{a}\right)\left[\frac{4}{3}+\frac{1}{4}\left(\frac{a}{t}\right)\right]$	$a\left[\frac{32+6\left(\frac{a}{t}\right)}{13+8\left(\frac{a}{t}\right)}\right]$	$a\left[\frac{4}{11+2\left(\frac{a}{t}\right)}\right]$
Recommended Range of Applicability 1.0<(α/τ)<0.1			

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Open Loop Tuning Rules (Continued)

Minimum ITAE				
Controller Type	Type of Response	K_c	τ_I	τ_D
P	Disturbance	$\frac{0.49}{K}\left(\frac{t}{a}\right)^{1.084}$	___	___
PI	Setpoint Tracking	$\frac{0.586}{K}\left(\frac{t}{a}\right)^{0.916}$	$\frac{t}{\left[1.03-0.165\left(\frac{a}{t}\right)\right]}$	___
PI	Disturbance	$\frac{0.859}{K}\left(\frac{t}{a}\right)^{0.977}$	$\frac{t}{0.674}\left(\frac{a}{t}\right)^{0.680}$	___
PID	Setpoint Tracking	$\frac{0.965}{K}\left(\frac{t}{a}\right)^{0.855}$	$\frac{t}{\left[0.796-0.147\left(\frac{a}{t}\right)\right]}$	$0.308t\left(\frac{a}{t}\right)^{0.929}$
PID	Disturbance	$\frac{1.357}{K}\left(\frac{t}{a}\right)^{0.947}$	$\frac{t}{0.842}\left(\frac{a}{t}\right)^{0.738}$	$0.381t\left(\frac{a}{t}\right)^{0.995}$
Recommended Range of Applicability $1.0<(\alpha/\tau)<0.1$				

Things to watch out for:

(Open Loop Tuning)

- Most tuning rules have a suggested range of applicability based on the ratio of α/τ. Check to make sure the tuning rule is applicable before using.
- These tuning rules do not work for integrating processes. (level control for example)
- Make sure the PID equation your DCS uses is consistent with the standard form. If it is not transform the tuning constants to the appropriate form for your DCS.

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$$Output = k_c\left[\varepsilon(t) + \frac{1}{t_I}\int_0^t \varepsilon(t)dt + t_D\frac{d\varepsilon}{dt}\right] + C$$

- Some DCS systems use scaled values in the PID equation. If so tuning constants based on process engineering units may be incorrect.

- Steps should be made around the expected operating point.
- Steps should be made in both directions. Dynamics are very often directionally dependent.
- If the system is nonlinear steps should be made around the most sensitive (highest K value) part of the expected operating range. If this is not done it is possible for the controller to become oscillatory or even unstable when controlling in this region.
- Different tuning rules are based on different performance criteria. Select the one that most closely represents your desired response
- Remember these tuning rules are based on approximate models and thus should be a starting point in the tuning process.
- Beware of derivative action
  - Derivative action is very sensitive to process noise.
  - If setpoint changes will be made to the process the controller should be doing derivative action on measurement not error. If the derivative action is on error the output of the controller will spike when setpoint changes are made.
  - Derivative action is best suited for processes with significant deadtime and lag.

Closed Loop Tuning Rules

Ziegler-Nichols closed loop tuning is based on stability margins. To identify process parameters:

1. Turn off both integral and derivative action in the controller. This can usually be accomplished by putting zeros in the integral and derivative tuning parameters.
2. Set the proportional gain (K_c) to a small value.
3. Put the controller in Auto mode.
4. Make a small step in the controller setpoint.
5. Observe the process response.
6. If the controller does not continually cycle (stability limit), increase the controller gain (K_c) and repeat from step 4.
7. Once the controller continually oscillates, the controller gain is the ultimate gain K_{cu}.
8. Measure the period of the cycle and this is the ultimate period P_u.

Ziegler-Nichols Stability Margin			
Controller Type	K_c	τ_I	τ_D
P	$0.5K_{cu}$	___	___
PI	$0.45\ K_{cu}$	$\frac{P_u}{1.2}$	___
PID	$0.6K_{cu}$	$\frac{P_u}{2.0}$	$\frac{P_u}{8.0}$

K_{cu} = Ultimate gain (Minimum gain with P-only control that causes system to cycle continuously)

P_u = Ultimate period of oscillation

Things to watch out for (Closed Loop Tuning):

- Many processes should not be tuned using stability limit tuning rules. To get the process parameters the system has to be brought to the brink of instability. This is very often undesirable and sometimes even dangerous.
- Recognize that with P-only control there will be steady state offset.
- Do not let the manipulated variable saturate high or low.
- Use the smallest controller gain that gives marginal stability as the ultimate gain.
- Make sure the PID equation your DCS uses is consistent with the standard form. If it is not transform the tuning constants to the appropriate form for your DCS.
- Standard Form:

$$Output = k_c\left[\varepsilon(t) + \frac{1}{t_I}\int_0^t \varepsilon(t)dt + t_D\frac{d\varepsilon}{dt}\right] + C$$

- Some DCS systems use scaled values in the PID equation. If so tuning constants based on process engineering units may be incorrect.
- Steps should be made around the expected operating point.
- Steps should be made in both directions. Dynamics are very often directionally dependent.
- If the system is nonlinear steps should be made around the most sensitive (highest process gain value) part of the expected operating range. If this is not done it is possible for the controller to become oscillatory or even unstable when controlling in this region.
- Cycle won't always be symmetric due to different dynamics for process steps up Vs down.
- Tuning rules should be a starting point in the tuning process.
- Beware of derivative action
  - Derivative action is very sensitive to process noise.
  - If setpoint changes will be made to the process the controller should be doing derivative action on measurement not error. If the derivative action is on error the output of the controller will spike when setpoint changes are made.
  - Derivative action is best suited for processes with significant deadtime and lag.

Dale's Closed Loop PI Tuning Technique

The concept with Dale's tuning is to take advantage of the form of the PID equation.

$$Output = k_c\left[\varepsilon(t) + \frac{1}{t_I}\int_0^t \varepsilon(t)dt + t_D\frac{d\varepsilon}{dt}\right] + C$$

Note that the integral and the derivative actions in the controller are dependent on the value of k_c but the proportional action is not dependent on the integral (t_I) or derivative (t_D) tuning. If we can first get a value of k_c that we know is stable but aggressive we can then easily determine a value for t_I that works well. Derivative can be added if the dynamics of the process are slow and the process value is not noisy.

1. Understand your process. You should have a reasonable knowledge of the process characteristics (self regulating, integrating). In addition, you should have a reasonable knowledge about how much deadtime, lag, inverse response etc.
2. Decide what type of controller response you would like. Overdamped, underdamped, critically damped, etc. based on control objectives.
3. Unless the process has significant delays or lags don't use derivative action.
4. Set the integral and derivative tuning constants to zero. This should disable integral and derivative action of the controller.
5. Set the controller mode to Auto.
6. Make a small step change in the setpoint of the controller.
7. Watch the response.
   - If the process value oscillates (underdamped) decrease the controller gain and repeat step 5.
   - If the process value does not oscillate increase the controller gain and repeat step 5.
   - The goal is to find the controller gain where the process is critically damped (K_{cd}). This is where the process response goes from an overdamped to an underdamped response.

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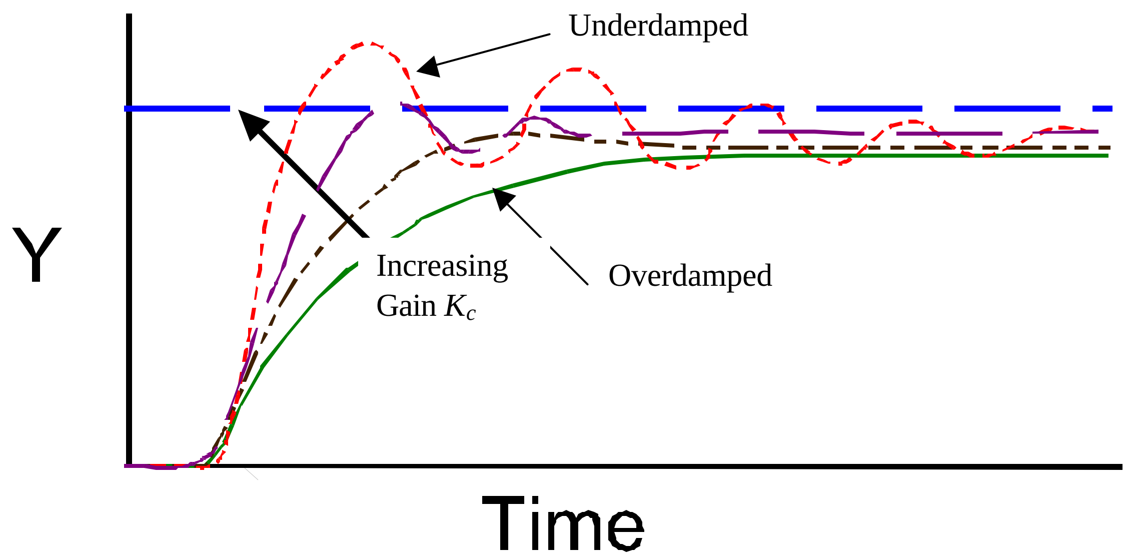
1. Once K_{cd} has been found set the final gain of the controller based on desired response.
   - $K \approx 1.2K_{cd}$ if an underdamped response is desired.
   - $K \approx 0.8K_{cd}$ if an overdamped response is desired.



2. Once the controller gain is set, enter a large integral tuning parameter (t_I). This represents a small amount of integral action. Decrease t_I to get the desired elimination of steady state offset. Remember, in most cases the purpose of integral action is to eliminate offset. As you decrease t_I at some point you will notice that the controller becomes more oscillatory. If the controller was overdamped when you started and becomes underdamped, you know it is because of the integral action. Thus you have reached the limit and should back off on the integral action.

That's it.

Derivative action can be added if desired. If the process value signal is **not** noisy and the derivative is on the measured PV and not on the error, derivative action should stabilize the controller. In general, if derivative action is added, the controller gain (K) can be increased and the integral term (t_I) can be decreased. **BEWARE: derivative action often behaves poorly on industrial processes.**

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