Instrumentation & Control - Course 136

CONTROL MODE SETTINGS

The quality of control obtained from a particular system depends largely on the adjustments made to the various mode settings.

Many control loop components change their phase shift or gain under different load conditions. Some practical examples to demonstrate this concept of nonlinearity would include:

(a)   level control in a non uniform tank,

(b)   flow control from a square root scale,

(c)   variable valve ΔP as flow increases.

As a result of this nonlinearity, controller adjustments which provide good stability at one load may produce severe cycling at an increased or decreased load.

One solution to this problem is to compromise between stability and recovery time. Control adjustments are made to provide slight cyclic recovery under the most unstable load and set point conditions. This will provide less than optimum recovery under other load and set point combinations but ensure stable response.

Two general methods of controller tuning to provide optimum control of a given process are:

1.   Ziegler and Nichols Method (ultimate sensitivity).

2.   Process Reaction Curve Method.

Ultimate Sensitivity Method

This is a method of determining the optimum controller settings by referring to a set of equations developed by Ziegler and Nichols. The ultimate sensitivity method was derived empirically by examining the general characteristics of many industrial control loops.

The fundamental information required is that proportional band value which will cause constant amplitude process cycling and the resulting period of such a cycle. In order to obtain this cycling, the process is first brought to the set point on manual control with reset and derivative modes eliminated. (0 RPM, 0 min.) Control is then switched to automatic and the proportional band is narrowed until the process just cycles with constant amplitude following an applied disturbance. (Set point shift.) The process is now in a state of marginal stability so that the loop gain is known to be one and the phase lag is 180 degrees. The appropriate Ziegler and Nichols (Z/N) formula can then be used to find the optimum controller settings.

Ziegler and Nichols Formula

Ultimate Proportional Band (PB_u): That proportional band setting which results in constant process cycling following a disturbance.

Ultimate Period (P): The period of the constant amplitude process cycle.

Proportional Only

$PB = 2\ PB_u$

Proportional Plus Reset (PI)

$PB = 2.2\ PB_u$

$$R = \frac{P}{1.2}\ (MPR)$$

Proportional Plus Reset Plus Derivative (PID)

$PB = 1.6\ PB_u$

$$R = \frac{P}{2}\ (MPR)$$

$$D = \frac{P}{8}\ (MIN)$$

These general formulas can be related to the theoretical control modes developed in lesson 136.00-2.

Consider a process cycling under straight proportional control. The proportional band setting must be the ultimate proportional band and the loop gain is one.

In order to achieve the quarter decay ratio from constant cycling, each half cycle must have one half the magnitude of the previous half cycle. (Visualize that the controller response to the positive deviation results in the subsequent negative deviation). The loop gain must be reduced from one to one half. The effect of the control response to a positive deviation will be a negative deviation of one half the magnitude. The resulting positive deviation will now be one half the negative deviation so that the current positive deviation is a quarter of the original - quarter decay ratio.

The loop gain is halved by halving the controller gain which would require doubling the ultimate proportional band.

Recall the general relation: $\%PB = \dfrac{100}{Gain}$

Halving the control gain: $\%PB = \dfrac{100}{.5 \; Gain} = 2 \times \dfrac{100}{Gain}$

Straight Proportional: $\%PB = 2 \; PB_u$

The operating proportional band must be widened when reset is added to correct for the destablizing effect of reset. (Increased phase lag.)

Notice that the operating proportional band will be 10% wider for PI control than for straight proportional. (PB = 2.2PB$_u$). The proportional band can be narrowed when derivative mode is added since closer control will be possible without danger of instability. (Rate introduces a phase lead.) Notice that the proportional band setting for a three mode controller will be approximately 80% of the setting required for straight proportional. (PB = 1.6PB$_u$.)

From empirical studies it has been found that the maximum lead from a proportional plus derivative controller will have a practical limit of 40 degrees. This phase angle can be used to calculate a general derivative time compared to the cycle period.

Proportional Plus Derivative

$$Tan \; (\phi) = \frac{2\pi D}{P}$$

$$Tan \; (40) = \frac{2\pi D}{P}$$

$$.839 = \frac{2\pi D}{P}$$

$$D = \frac{.839}{2\pi} = \frac{P}{7.49}$$

For ease of recall and to ensure stability, the more conservative time of P/8 could be selected. This would correspond to a phase lead of 38 degrees which is still reasonably close to the practical limit.

The maximum lag that a proportional plus reset controller should contribute at cyclic conditions is known to be 11 degrees. The general reset time can be calculated using the following phase relationship.

$$\text{Tan} \, (\theta) = \frac{P}{2\pi R}$$

$$\text{Tan} \, (11) = \frac{P}{2\pi R} = .194$$

$$R = \frac{P}{2\pi(.194)} = \frac{P}{1.22} \quad (MPR)$$

The lead contribution of a three mode controller should be approximately 25 degrees at process cyclic conditions. The physical lead limit of 40 degrees would still apply to the derivative component and reset rate can be increased until the total lead of the combination is reduced to 25 degrees. Notice that more reset effect is possible with PID control than with PI control due to the corrective action of derivative mode.

$$\text{Tan} \, (25) = (\frac{2\pi D}{P} - \frac{P}{2\pi R})$$

$$.466 = \frac{2\pi(P/8)}{P} - \frac{P}{2\pi R}$$

$$.466 = \frac{2\pi}{8} - \frac{P}{2\pi R}$$

$$\frac{P}{2\pi R} = .319$$

$$R = \frac{P}{2} \quad (MPR)$$

Example

Determine the optimum three mode settings using the Z/N formula for a process which cycles uniformly 3 times in 27 minutes with a proportional band setting of 65%.
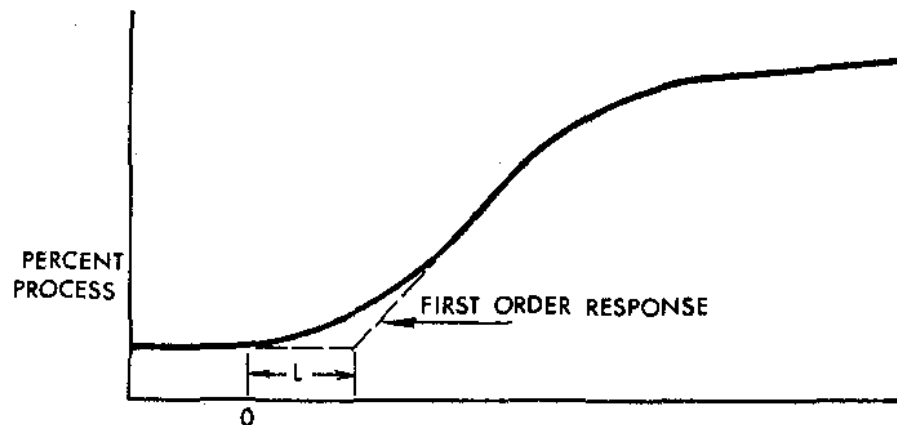
$$\%PB = 1.6PB_u = 1.6(65) = 104\%$$

Ultimate Period $= \dfrac{27}{3} = 9$ minutes

$$R = \dfrac{P}{2} = \dfrac{9}{2} = 4.5 \text{ MPR } (.222 \text{ RPM})$$

$$D = \dfrac{P}{8} = \dfrac{9}{8} = 1.125 \text{ minutes}$$

Reaction Curve Method

A multicapacity system response to a step disturbance can be represented in general as a dead time and a first order response. The larger time constant is able to dominate the response, and the delay due to small time constants will approach dead time.

The procedure requires that the control loop be opened at the final actuator. This can be achieved by placing the controller on manual. A step change input to the process can now be achieved by changing the regulated pressure applied to the valve actuator a discrete amount.
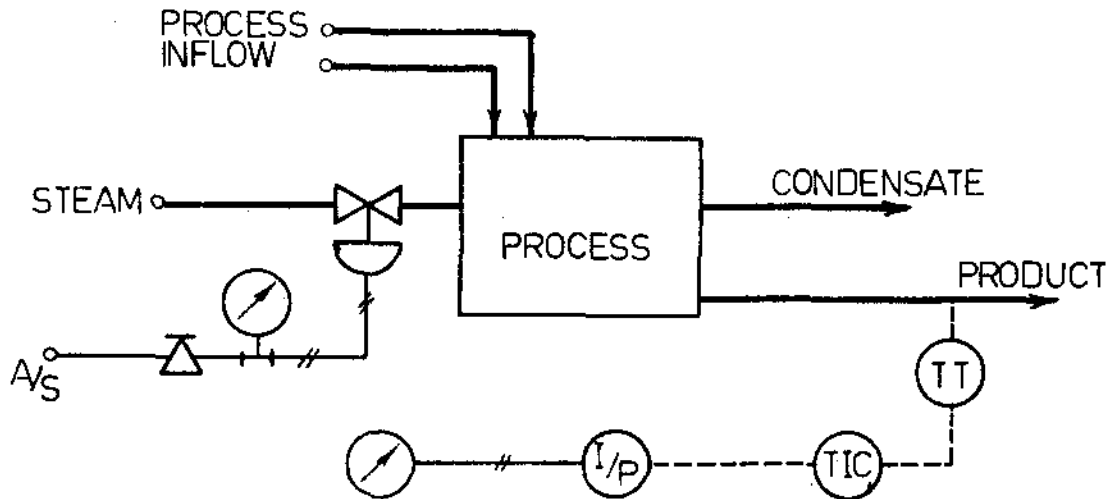
The resulting process change can be noted with respect to time, or a trend recorder could be activated to record the process reaction to the step change. The reaction curve can then be analyzed to find the effective dead time (L) and the maximum slope or maximum reaction rate in percent change of process per minute (%C). In order to appreciate the reaction curve method of controller tuning it would be worth-while to review the concepts of capacitance and dead time.

Capacitance

The capacitance of a system is the ratio of the system capacity to some reference variable. Consider level control in a tank, the capacitance of the tank can be found by examining volume wrt level.

A large capacitance system will not be very sensitve to small changes in input. A given step change in valve position in a large capacitance system will result in a relatively small amplitude process response. Such a process can be said to be a low gain application. Consider the simplification that the loop gain must be less than one (at the 180 degrees lag frequency) to ensure stability. (Control gain X process gain <1). A relatively narrow band control could be utilized on a low gain process control system.

If the process was a low capacitance system it would be sensitive to small changes in input. A given step change in valve position in a small capacitance system will result in a relatively large amplitude process response. The process can be said to be a high gain application. To ensure stability a wider proportional band must be used.

The capacitance of a system can be estimated by testing the system with a step change in valve position. A response factor could be determined to relate percent change in process to a particular change in valve position. The larger this response factor is, the smaller the capacitance of the system must be and accordingly the wider the operating proportional band must be to ensure stable control.

%PB α (Response Factor)

General Rule: increase process capacitance, narrow the %PB.

Dead Time

Consider a temperature control system that seems to work adequately with a loop gain of one. The mixed water temperature is being controlled to the desired set point in a stable fashion by regulating the inflow of hot water.
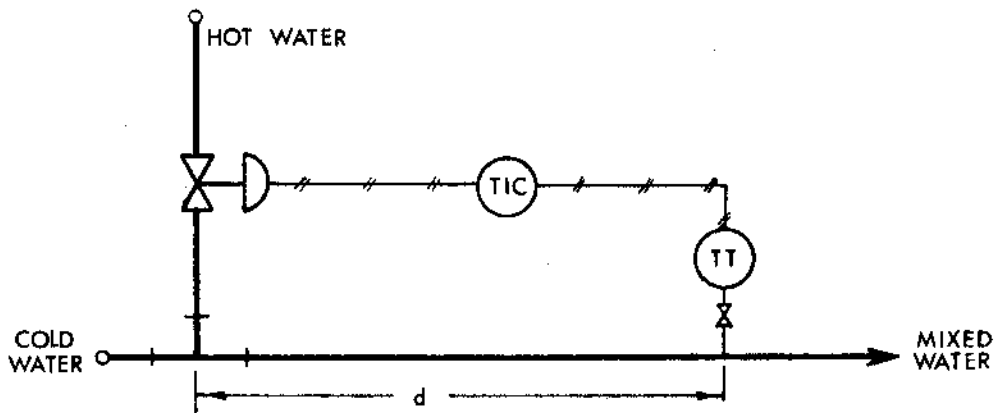
The location of the temperature sensor introduces a dead time element into the control system.

ie, the time to transport the mixed water from the mixing tee to the detector.

Assume a slug of cold water enters the system and pulls the mixed water temperature down.

This slug passes by the sensor causing a decrease in transmitter signal applied to the controller. Note at this time that the water at the mixing tee is back to normal temperature, the cold slug is located at the detector. The controller responds by opening the control valve more and adding more hot water to the system raising the mixed water temperature until the cold slug has passed by the sensor. The control system has caused a slug of hot water to be admitted to the system which in turn will flow past the sensor. The controller will respond to the hot slug by decreasing the hot water inflow to the system causing a second cold slug to be introduced.

ORIGINAL COLD SLUG   CONTROL INDUCED HOT SLUG   CONTROL INDUCED COLD SLUG
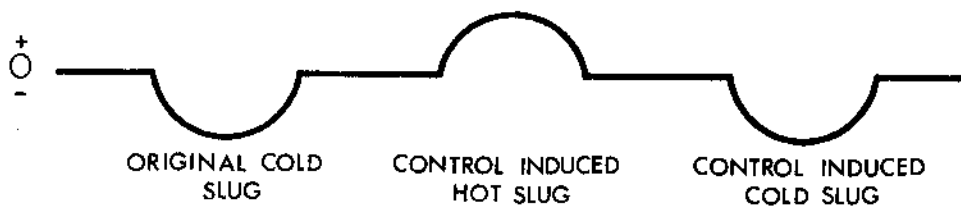
This process response will smooth out to approximate a sine wave. The net result will be that the control system will maintain the disturbance introduced cycle because the dead time has caused the correction to be made well after the upset occurred.

This constant amplitude oscillation can be attenuated by decreasing the controller gain. The system will now provide a controlled underdamped response with the wider proportional band.

General Rule: increase system dead time, widen the %PB.

From examining capacitance, it was found that the %PB setting must be proportional to the system response factor. Including dead time in the consideration would require that the %PB setting be proportional to the dead time interval.

%PB α (Response Factor x Dead Time)
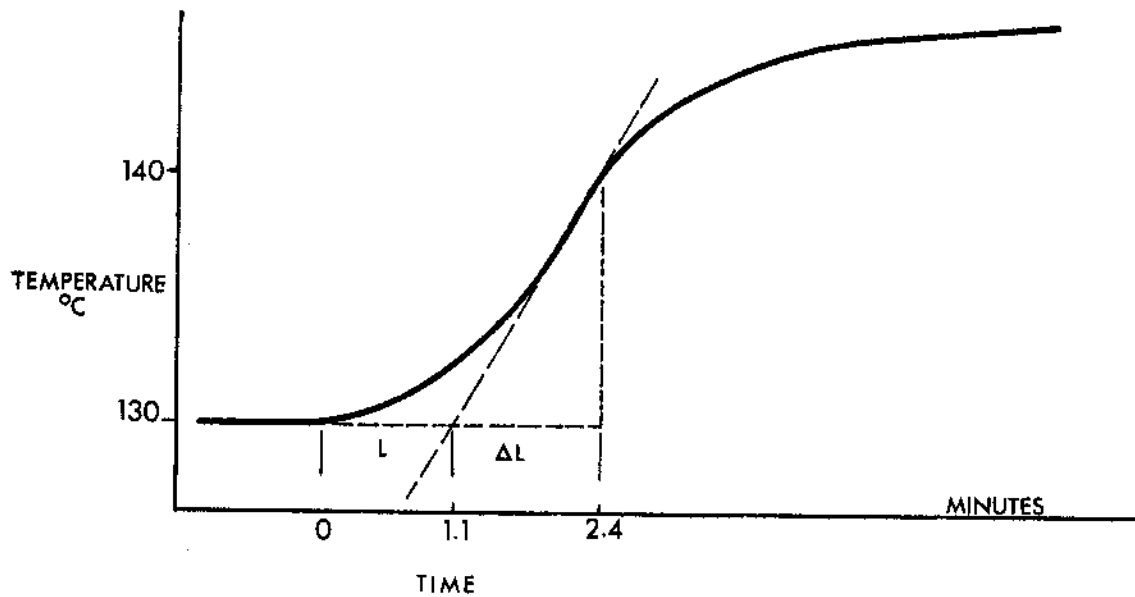
The percent change in valve position applied to the system to cause a step response must be noted. (%ΔV).

The resulting process reaction curve can be examined to determine the effective dead time (L), and the maximum slope of the reaction curve. A straight line is drawn tangent to the point of inflection on the reaction curve, a second straight line is drawn horizontally from the initial process value. The intersect of these two straight lines will define the effective dead time (L) wrt the step initiation.

The slope of the tangent line, which is the maximum slope of the reaction curve will provide the process response rate factor.

$$\left(\%C = \frac{\% \Delta P}{min} \right)$$

Once the dead time approximation, the percent change in valve position, and the process reaction rate is known; then the applicable reaction rate formula can be used to determine the optimum mode settings.

Reaction Curve Formula

Proportional

$$\%PB = \frac{100(\%C)(L)}{\% \Delta V}$$

Proportional Plus Reset

$$\%PB = \frac{110(\%C)(L)}{\% \Delta V}$$

$$R = \frac{L}{.3} \quad (MPR)$$

Proportional Plus Reset Plus Derivative

$$\%PB = \frac{83(\%C)(L)}{\% \Delta V}$$

$$R = 2L \quad (MPR)$$

$$D = \frac{L}{2} \quad (min)$$

Example

Refer to the previous reaction curve sketch in the notes. This process response was achieved with a 12kPa increase to a 20 - 100 kPag valve actuator. The controlled range of the process is 100 - 200 degrees C. Determine the three mode controller settings using the reaction curve method.

Calculate the percent change in valve position:

$$\% \Delta V = \frac{12}{80} \times 100 = 15\%$$

Calculate the percent change in process per minute:

$$\%C = \frac{10}{2.4 - 1.1} = \frac{10}{1.3} = 7.69 \ \%/min.$$

Determine the effective dead time:

from the curve, L = 1.1

$$\%PB = \frac{(83)(\%C)(L)}{\%\Delta V} = \frac{83(7.69)(1.1)}{15} = 46.8\% \approx 47\%$$

$$R = 2L = 2(1.1) = 2.2 \ MPR$$

$$D = \frac{L}{2} = \frac{1.1}{2} = .55 \ minutes.$$

Zielgler and Nichols devised the reaction curve method also as a result of empirical studies on a wide variety of systems. The ultimate sensitivity and reaction curve methods will give very similar results for a given application. The period of oscillation in a system will be approximately four times the effective dead time of the reaction curve for that system. If the dead time is much greater than the first order time constant (say six times), then only PI control should be used since derivative mode would compound the control problem. If the dead time is zero, then the %PB can be set to zero (on/off control) since the system can be characterized as pure first order and will not cycle.
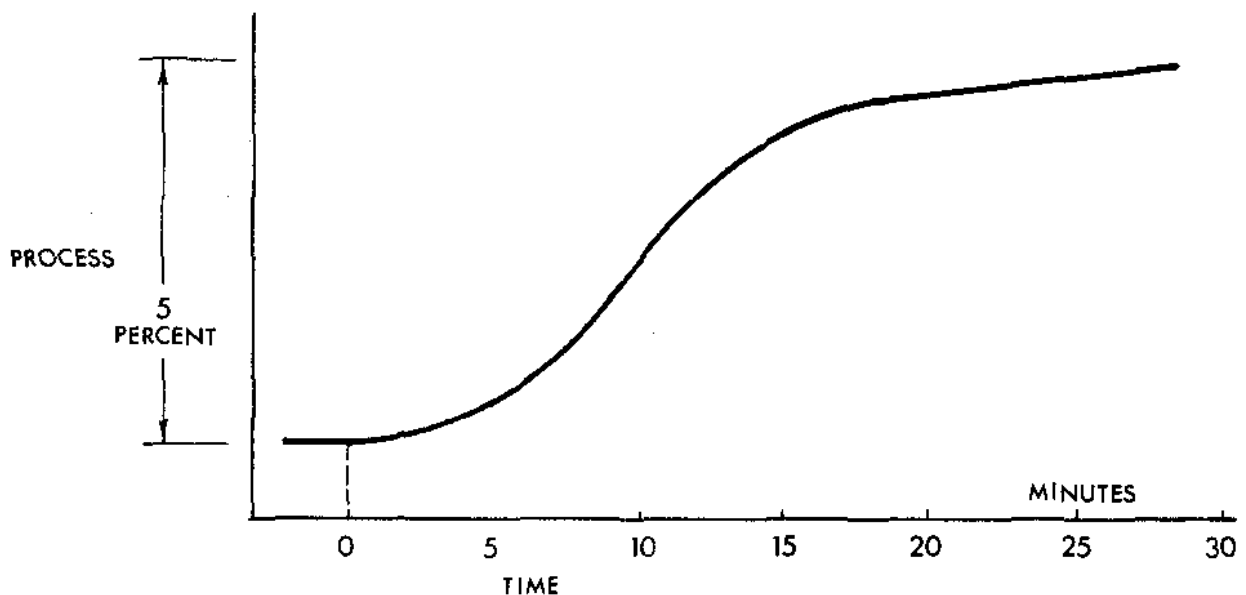
ASSIGNMENT

1. A three mode controller is to be tuned to a particular process which cycles 5 times in one half hour under critical proportional control. The $PB_u = 60\%$. Determine the control mode settings required using the Ziegler/Nichols method.

2. Repeat Question 1 with a process cycle time of 0.5 minutes. State the two mode combination which would seem to provide adequate control.

3. Repeat Question 2 for a process cycle time of 60 minutes.

4.   A process is analyzed by the reaction curve method and
the effective dead time is found to be zero minutes.
What will be the proportional band setting?

5.   Would a large capacitance, slow response process be con-
trolled with a wide band or a narrow band controller
setting?

6.   A control system is operating adequately under PI con-
trol with a 20%PB and 3MPR settings. A substantial cap-
acitance increase results from new constructon addition
to the system but the control settings are inadvertently
left unchanged.

When this system was subjected to a slight operational
disturbance the process cycled for a prolonged time
(with a 15 minute period) approaching marginal stab-
ility.   What recommendations would you make concerning
this system problem?

7.   Analyze the following reaction curve sketch to determine
the correct 3-mode control setting. A 2% valve change
was made to initiate the process response.

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