Introduction to the Process Control System

Definition of Terms

process - A physical or chemical state of matter or conversion of energy; e.g., pressure, temperature, speed, electrical potential.

controller - A device or program which operates automatically to regulate a controlled variable.

auto/manual mode - Automatic mode of a controller assumes the feedback (or feedforward path) is complete or unbroken and the controller is comparing the set point to the process variable. In manual mode, the feedback (or feedforward) path is broken, and while the controller may still register the process variable, the output is manipulated by an operator.

proportional band - The change in input required to produce a full range change in output due to proportional control action.

integral control action (reset) - Control action in which the output of the controller (this is in fact the input to the process) is proportional to the time integral of the error input, i.e., the rate of change of output is proportional to the error input.

derivative control action (rate action) - Control action in which the output of the controller (this is in fact the input to the process) is proportional to the rate of change of input.

final control element - An instrument that takes action to adjust the manipulated variable in a process. This action moves the value of the controlled variable back towards the set point.
set point - An input variable which sets the desired value of the controlled variable. The input variable may be manually set, automatically set, or programmed. It is expressed in the same units as the controlled variable.

controlled variable - The variable which the control system attempts to keep at the set point value. The set point may be constant or externally adjusted.

process variable - In the treatment of material, any characteristic or measurable attribute whose value changes with variations in prevailing conditions. Common variables are flow, level, pressure, and temperature. **The controlled variable is a process variable.**

manipulated variable - The part of the process that is adjusted to close the gap between the set point and the controlled variable.

steady state - A characteristic of a process variable at equilibrium where no further changes take place.

transient - A process variable that is in transition. i.e. not at sterady state.

Elements of a Process Control System

In automatic mode, the controller compares the actual value of the variable being controlled (controlled variable) to the target value (set point). The error between the set point and the controlled variable is then input to the controller. The controller then outputs a signal to try to minimize the error by adjusting a variable (manipulated variable) that will cause the controlled variable to come back toward set point.

The controller can also operate in manual mode. In manual mode, the feedback path is opened up and thus incomplete. While the controller may still register the process variable, the output of the controller is manipulated by an operator.

A direct acting controller generates an output signal that increases when the controlled variable increases. A reverse-acting controller generates a decreasing output controller signal when the controlled variable increases.

A controller's ability to correct for and minimize an error can be disabled. When this occurs, the controller's output is fixed and changes only if a manual adjustment is made. When the controller is set to this mode, it is said to be in **manual mode**. The control system is said to be **open-looped**; that is, no feedback of the level signal and no corrective action takes place.

Block Diagram of Feedback Control System

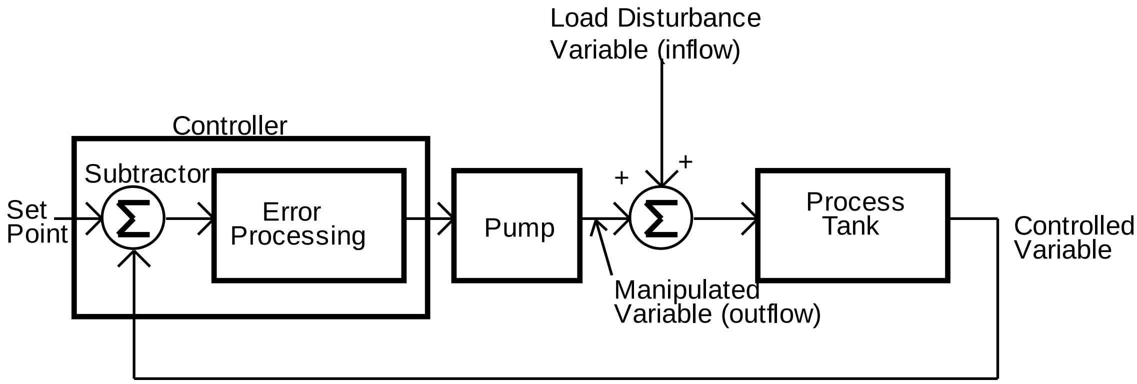


Fig. 1-1

Tank Level Control System

The level control system shown in Fig. 1-2 is an example of a feedback control system.

The controlled variable is the level. This value may be expressed directly in engineering units (feet, metres, centimetres, etc.) or as a percent of the full scale calibrated range.

The set point is the desired level in the tank. It may also be expressed in engineering units or percent of full scale calibrated range.

The manipulated variable is the outflow that is changed by the controller output adjusting the positive displacement pump output.

The final control element is the modulating (continuously adjustable) positive displacement pump.

The process is the tank (sometimes the final control element is considered part of the process).

The disturbance is any change either positive or negative in the input flow to the tank. This is only one of the many disturbances associated with this process. Any outside influence that would cause the tank level to change would be considered a disturbance. These might include change in the temperature of the fluid or change in the downstream pressure of the valve. Refer back to Fig. 1-1 for the block diagram of the system.

Tank Level Control System

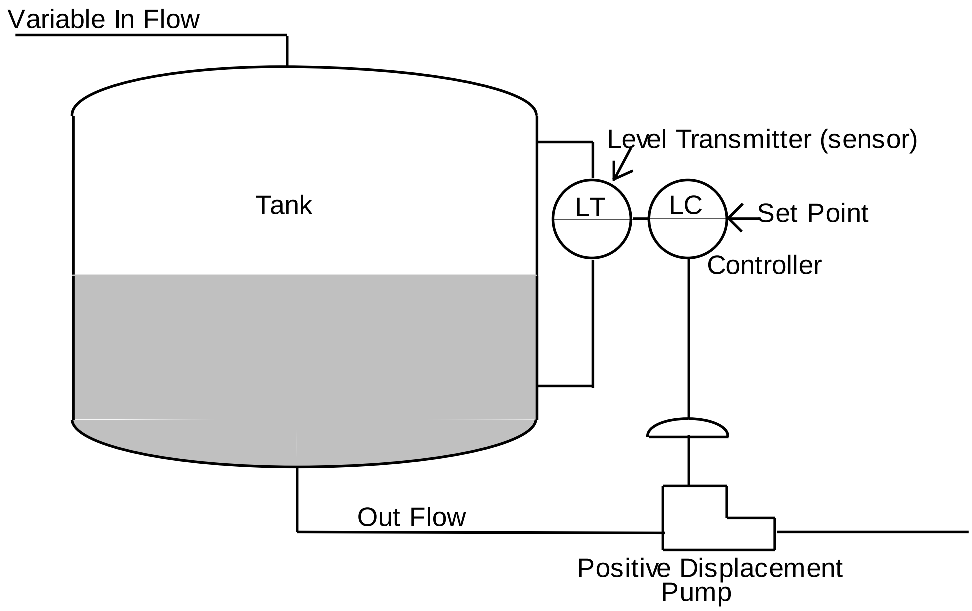


Fig. 1-2

Process Gain and Dynamics

Definition of Terms

process dynamics - A set of dynamic interactions among process variables in a complex system, as in a petroleum refinery or chemical process plant. The dynamics of a process characterize the process's time response for different input stimuli such as step changes, impulses, and ramps. Probably the most often used input is the step change.

process gain - The process gain refers to the process sensitivity; That is, a sensitive process will have a high process gain, producing a large change in the output process variable for small changes in input variable. The process gain can be either expressed as a dimensionless constant (% of calibrated span/% of calibrated span) or in engineering units.

time constant or lag time - Refers to the dynamic element of a process that results in a response that falls behind the change in input; that is, if a step input change occurs to a process, the time constant or lag time results in a response that begins to change at the instant the step change occurred but that takes some time before reaching a steady-state value. The curve of the response will be affected by how many time constants are in the process.

dead time - The interval of time between initiation of an input change or stimulus and the start of the resulting response.

step input change - A change to the input to a process such that the input rises or falls from one input value to another almost instantly.

first-order system - A system definable by a first-order differential equation. A first-order system contains only one time constant and is characterized by a step response that is exponential reaching 63.2% of its final steady-state value in a time equal to the time constant.

second-order system - Two first-order systems cascaded together will form a second-order system. A step change to this type of system will result in a further delay to the response, making it look somewhat S-shaped. This definition refers to systems that are over or critically damped. Most processes behave as overdamped systems.

overdamped response - A response to a step change that contains no oscillations in reaching a steady state.

underdamped response - A response to a step change that contains oscillations in reaching a steady state.

critically damped response - The fastest response to a step change that contains no oscillations.

range - The set of values over which measurements can be made without changing the instrument's sensitivity. The extent of a measuring, indicating, or recording scale.

span - The difference between maximum and minimum calibrated measurement values. Example: an instrument having a calibrated range of 20 - 120 has a span of 100.

Dynamic and Steady-State Behavior

A process, whether it is a combustion furnace, a chemical reactor, a distillation tower, or a direct current motor, can be characterized by its steady-state behavior, and dynamic behavior.

The steady-state behavior refers to the final output value that the process variable reaches after an input change to the process has occurred.

The dynamic behavior refers to the manner and time taken for the process variable to reach steady state.
Throughout this chapter we refer to the process variable rather than the controlled variable. The controlled variable is a process variable being controlled by a feedback

control system. Since this chapter only discusses the characteristics of processes that are not being controlled, no reference is made to the controlled variable.

Characterizing the Dynamic Behavior of a Process Using the Step Input

Many types of input changes can be used when trying to characterize an output, but in industrial processes the simplest and most often used is the step change. This is an instantaneous change from one input value to the next (see Fig. 2-1).

Step Change

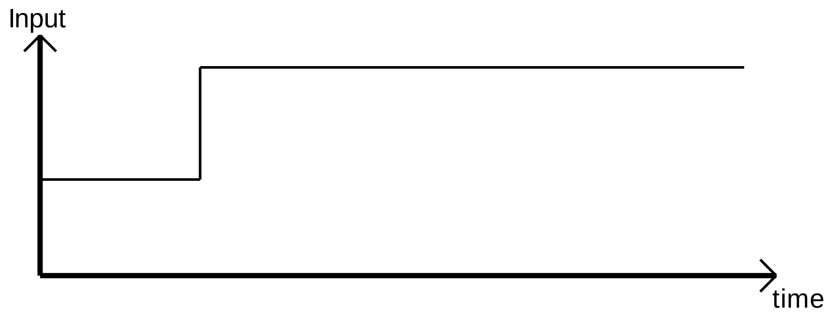


Fig. 2-1

In an industrial process heater, for example, for a given feedstock flow, a fuel gas firing rate will result in a certain temperature on the outlet of the coil of the furnace (see Fig. 2-2).

Industrial Process Heater

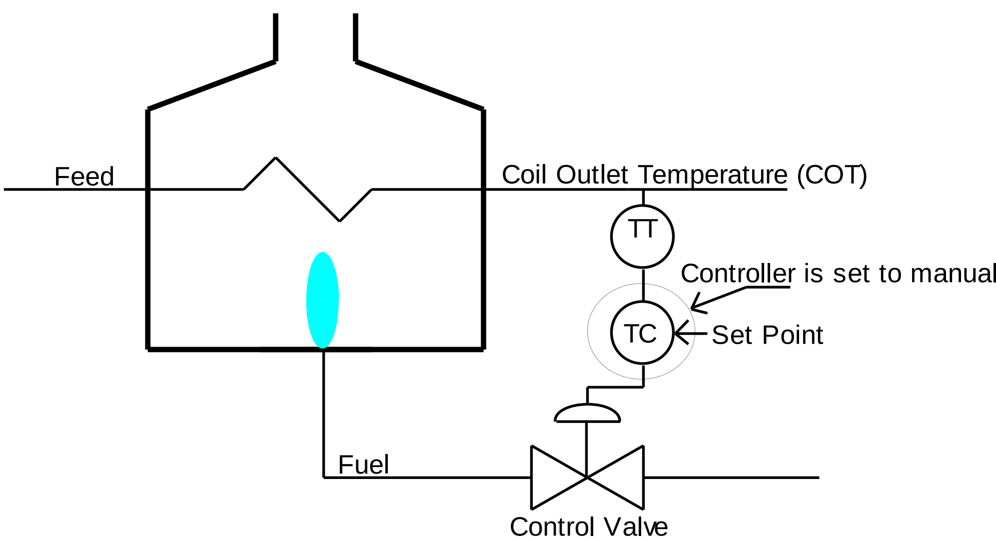


Fig. 2-2

If we raise the fuel gas firing rate, we will also raise the outlet temperature of the coil. The step input is the sudden change in fuel gas flow and the process output is the response on the coil outlet temperature.

The response curve may look similar to the response curve shown in Fig. 2-3.

Time Lags (Time Constants) and Dead Time

The factor that determines the characteristic response is the number of time lags and the dead time associated with the process. In the case of the furnace, there would be a lag associated with the time that the additional heat from the increased fuel flow is uniformly distributed throughout the furnace fire box. There would also be a lag associated with the time taken for this higher furnace fire box temperature to raise the temperature of the feed to a new steady-state temperature. There would also be a lag in the temperature sensor itself. That is, even if the furnace feed has reached a new steady-state temperature, the temperature sensor itself will not reach steady-state until some time later due to the thermal capacity of the sensor.

It is the number of lags and the relative difference in the size of the lags that determine the response characteristic of the coil outlet temperature.

Dead time is a dynamic element that delays the onset of the response due to the lags in the process.

Time lags are associated with capacitance in the process while dead time is associated with delay time or transportation time.

In our furnace example a dead time might be associated with the time that the increasing air temperature in the firebox takes to travel from the flame tip to the furnace coil tubes containing the feed.

Another dead time in the furnace is associated with the transit time from the outlet of the furnace to the location of the coil outlet temperature sensor. If the sensor were located a long distance from the furnace, any changes taking place in the furnace would not be sensed for some time later. That time would be equal to the distance between the furnace and the sensor divided by the velocity of the fluid (distance/velocity).

Process Gain

The ratio of the change in outlet temperature to the change in fuel gas firing is called the steady-state gain of the heater. The gain can really be thought of as a sensitivity. That is, if the process were very sensitive (high gain), a large change in coil outlet temperature would occur for a small change in fuel gas flow.

Process gain can be expressed in engineering units or as a ratio of % change in output full-scale calibrated span divided by percent change in input full-scale calibrated span.

In the following experiments the measurement ranges will not be in actual engineering units but rather in % of full scale. An easy way to imagine this is to think of a household thermometer. Suppose it has a range of -40 to +55 degrees Celsius. Then each Celsius degree represents 100/95%. That is 95 Celsius degrees is 100%. If we wanted to know what 60% of full scale would be for the thermometer, we must find out how many Celsius degrees this represents and then add it to -40; i.e., 60% represents 0.6 x 95 + (-40) or 17 deg C.

Response to Step Change

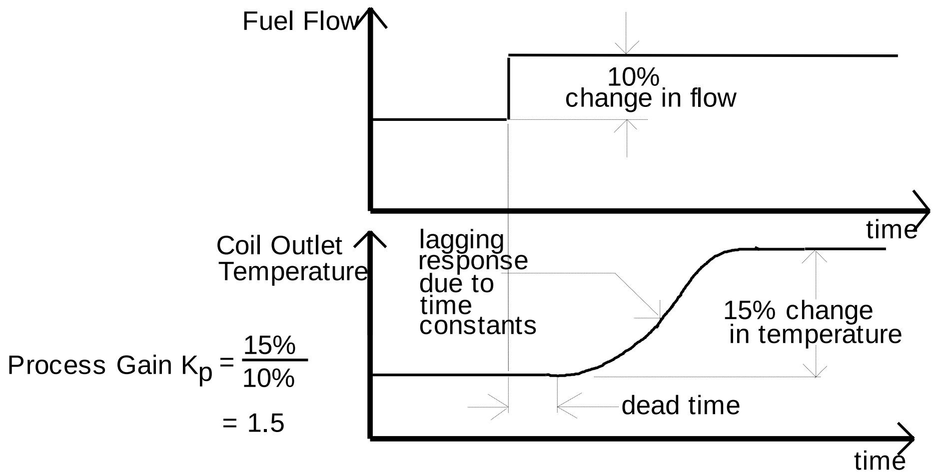


Fig. 2-3

The Proportional Controller

Definition of Terms

direct-acting controller - A controller in which the value of the output signal increases as the value of the input (measured variable or controlled variable) increases.

reverse-acting controller - A controller in which the value of the output signal decreases as the value of the input (measured variable or controlled variable) increases.

gain, proportional - The ratio of the change in output due to proportional control action to the change in input.

manual reset - An adjustment or bias that can manually be set by the operator. The manual reset directly adds to or subtracts from the output of the controller.

offset - A constant and steady state of deviation of the measured variable from the set point.

error - In a single automatic control loop, the set point minus the controlled variable for a reverse acting controller or controlled variable minus set point for a direct acting controller.

Elements of a Proportional Controller

Controllers can be implemented using a variety of technologies such as analog pneumatic or electronic and digital (single-loop microprocessor, computer implementing direct digital control, distributed control). In Appendix C a digital PID is implemented using GWBASIC. There are numerous reference sources that describe the components of the various types of analog controllers. The functionality of these various technologies in implementing PID control is quite similar, and the following three chapters will concentrate on the control concepts associated with PID rather than the hardware or software used in implementing the functions.

The simplest type of controller is the proportional-only (see Fig. 3-1). Mathematically it can be thought of as a pure gain. The term "proportional" comes from the fact that the change in output of the controller is proportional to the change in input. The input to the controller is an error signal generated from the difference between the set point and the controlled variable. The output is a constant times the input to the controller. This constant is sometimes referred to as controller gain.

Proportional Controller

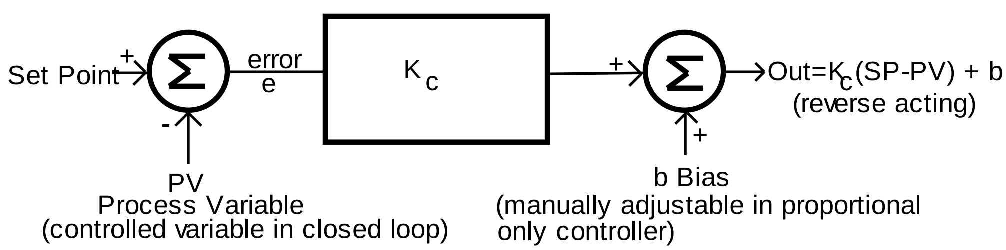
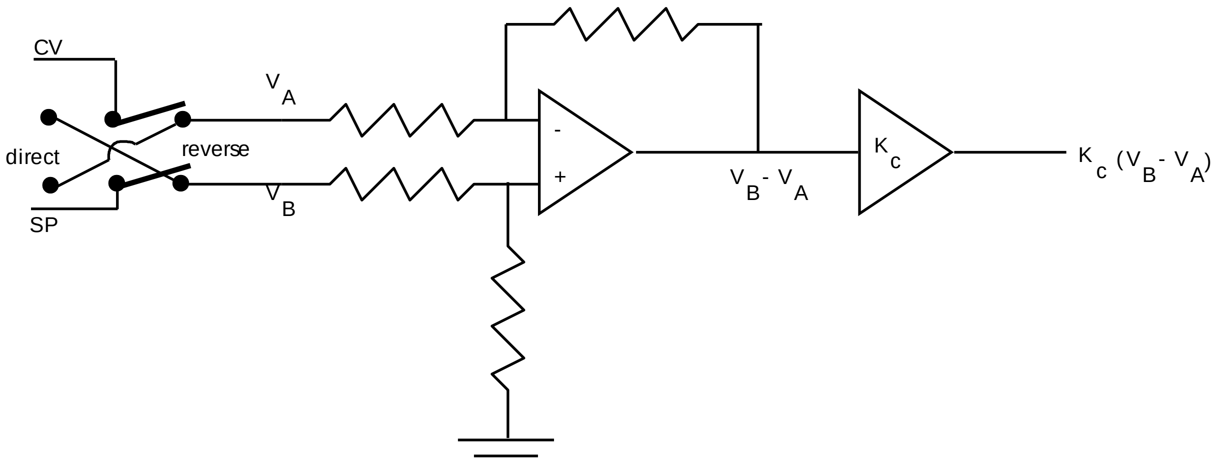


Fig.3-1

As mentioned in the definitions, error is equal to the set point minus the controlled variable for a reverse acting controller or controlled variable minus set point for a direct acting controller. In an actual implementation of an analog controller, this is simply accomplished using a switch to reverse the setpoint and controlled variable connected to the error amplifier. While some authors prefer to define the error as independant of the controller action while defining the gain as either positive or negative, AUTOSIM considers that the error definition changes depending on the action of the controller. This is consistent with what happens in an analog controller. The sketch below shows this switching arrangement for an analog controller.

Analog Controller Reverse/Direct Action Circuitry



Action	V_A	V_B	Error	Output
Reverse	CV	SP	(SP-CV)	K_C(SP-CV)
Direct	SP	CV	(CV-SP)	K_C(CV-SP)

The table above shows that for a direct acting controller, a set point greater than controlled variable results in a negative error, while for a reverse acting controller the error would be positive. The equations for the controllers are as follows:

$C_{out} = K_C(SP-CV)$ for reverse acting controller
$C_{out} = K_C(CV-SP)$ for a direct acting controller

From these equations, one can see that for a reverse acting controller, when the controlled variable CV increases, the controller output C_{out} decreases while for a direct acting controller the opposite occurs.

Proportional Band

The term "proportional band" is quite often used to describe the characteristics of the controller. The proportional band can be thought of as the percentage of full scale change in input signal that would cause a 100 percent change in output signal. Thus, a controller with a 20% PB would require a 20% change in input signal to affect a 100% change in output signal, while a controller with a 200% PB would change its output only 50% if the input were changed 100%.

It can be seen that a PB of 20% represents a gain of 5, while a PB of 200% represents a gain of 0.5 (gain = 100% / PB).

Controller Tuning

Mathematically, the proportional controller can be expressed as:

$$C_{out} = K_C e + b$$

where $\mathbf{C_{out}}$ is the output of the controller, K_c is the gain of the controller, **b** is bias, and **e** is the error or difference between the set point and controlled variable. In an industrial proportional controller the gain and bias are adjustable (the adjustable bias is sometimes called "manual reset"). The process of adjusting the gain is referred to as "tuning the controller".

3.2.4 The Proportional-Only Controller and Offset

Offset or steady-state error is a characteristic of a process using proportional only control.

For a simple level control system, offset can be explained as follows (see Fig. 3-2):

Level Control System

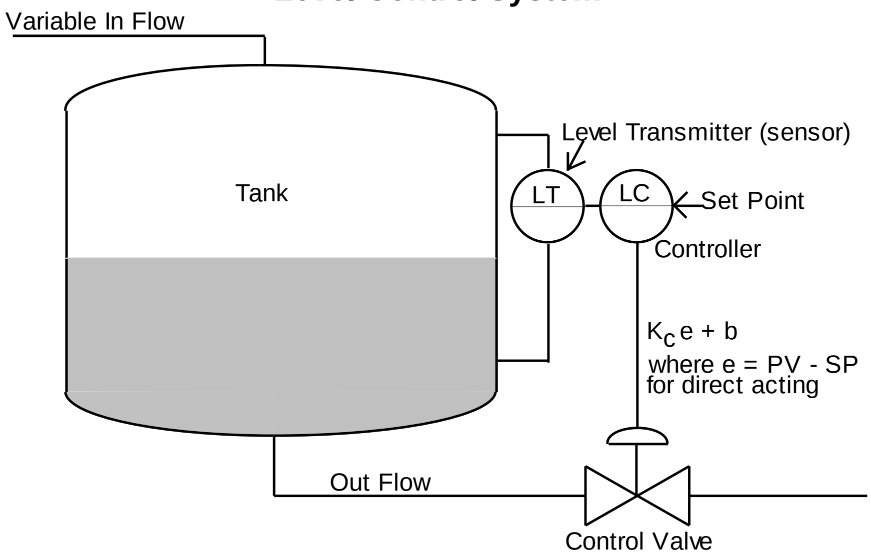


Fig.3-2

Suppose the controlled variable (level) happens to be at set point for a given inflow into the tank. The inflow and outflow must be equal if the tank level is not rising (you saw this in Chapter 1's simulation experiment). If the level is at set point, the error must also be zero. Then the signal going to the valve must be b from the controller (see equation in Fig. 3-2). This is the value of the controller output that keeps the valve open so the outflow exactly matches the inflow.

Now if the inflow is suddenly increased to a new steady-state value, the controller output's signal will increase due to the $\mathbf{K_C e}$ term of the equation. The controller will adjust the valve until the opening of the valve produces an outflow that exactly matches the new inflow. The level, however, cannot be at set point at the point where flow in and flow out are equal. This can be seen from the mathematics of the controller equation. Since the term $\mathbf{K_C e}$ is responsible for increasing (or decreasing) the controllers output, an error (e) must remain to maintain the new greater opening of the valve.

Offset can be reduced by decreasing the proportional band of the controller (increasing the gain). However, the limit on how much the proportional band (gain) can be decreased depends on the dynamic characteristics of the process.

Controller Action

Simply stated, a controller has direct action if an increasing controlled variable produces an increasing controller output. A controller has reverse action if an increasing controlled variable produces a decreasing controller output.

Looking at controller action in more detail, in the level control process, if the level were rising, the controller must open up the valve. If the valve's opening increases with an increasing controller output, then we say the controller's action needs to be direct-acting; that is, an increasing controlled variable (level) produces an increasing controller output change. Similarly, if the level were decreasing, the controller output would decrease to close the valve.

The action on a controller is usually switch or software selectable.

Proportional-Plus-Integral (PI) Control

Definition of Terms

seconds/repeat (minutes/repeat) - For a constant error, the time taken for the integral action to change (repeat) the output of the controller by the same amount that the proportional action changes the output for the same error.

reset windup - Saturation of the integral mode of a controller developing during times when control cannot be achieved, which causes the controlled variable to overshoot its set point when the obstacle to control is removed.

overshoot - A transient response to a step change in an input signal which exceeds the normal or expected steady-state response.

Requirement for Integral Action

In the previous chapter you found that while proportional control worked well on single time constant processes, it did not perform very well on processes with two or more significant time constants, especially if there was dead time in the process.
In attempting to eliminate offset (the difference between the set point and the controlled variable) by reducing the proportional band, you found that the process control system caused oscillations and could become unstable (controlled variable never reached a steady-state value).

Integral action in a controller acts on the error. **<u>As long as an error exists, integral continues to add to or subtract from the output of the controller until the error is eliminated</u>.**

Open-Loop Response of PI Controller

Shown in Fig. 4-1 is the output of the proportional-plus-integral controller for an error signal. This type of sketch is called an open-loop output response, because the PI controller isn't actually a part of a feedback control system; that is, the error is independently applied to the controller.

Open-Loop Response of PI Controller

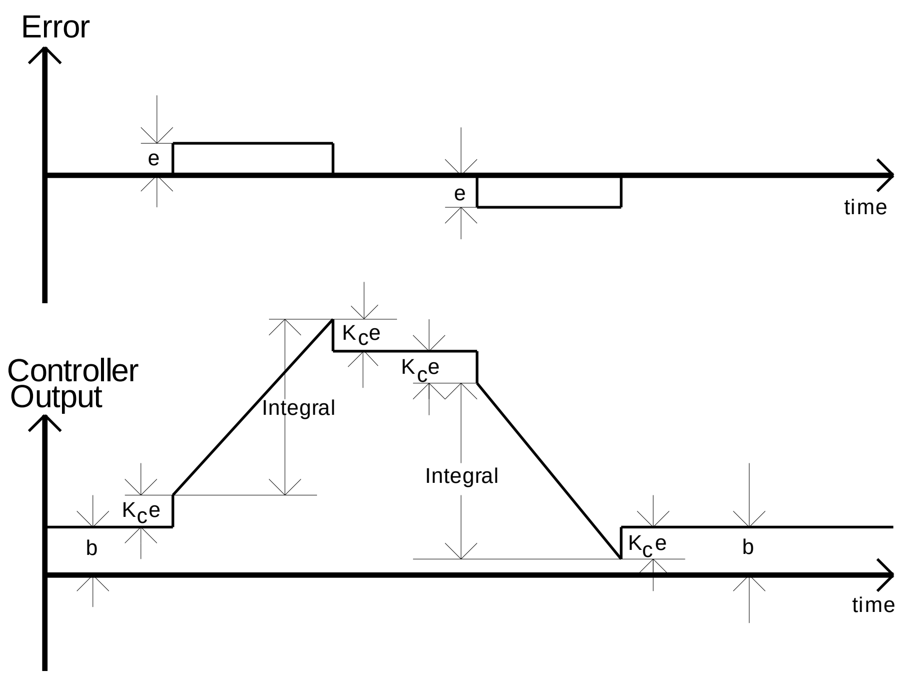


Fig. 4-1

Mathematics of PI Controller

The rate at which integral action changes the output of the controller is proportional to the magnitude of the error. In addition when the proportional band is changed, it also affects the integral action. Mathematically, integral action can be written as:

$$C_{out} = K_c e + \frac{K_c}{T_i}\int_{t_1}^{t_2} edt + b$$

where K_C is the gain, T_i is the integral time in seconds, and e is the error (difference between set point and controlled variable).

The evaluation of the expression for integral where the error is a constant equal to E is:

$$C_{out} = K_c E + \frac{K_c}{T_i} E(t_2 - t_1)$$

When this expression is evaluated for a constant error *e*, the integral will contribute, in a time equal to T_i seconds, a change in the output of the controller equal to the contribution in the controller output made by the proportional-only controller (i.e., $K_C E$); that is, the integral is repeating the action of the proportional only controller in T_i seconds. For this reason the units of integral are sometimes given in seconds/per repeat (or minutes/repeat - sec/repeat/60).

You should notice the following in the open-loop response for the PI controller (open-loop response is a convenient way to observe the characteristics of the controller; of course, in a closed-loop control system error is not constant):

- For a constant error input, the output will be a ramp with a slope proportional to K_C/T_i; that is, changing either T_i or K_C will alter the ramp rate and thus the integral action. The ramping rate is also proportional to the magnitude of the error.

- When a step change in error occurs, the output of the PI controller will produce a sudden output change equal to $K_C E$ followed by a ramp with slope equal to $(K_C/T_i)E$

- When the error switches to 0, the contribution of the proportional is removed, causing the output to suddenly drop. However, the output is held at this new steady-state value. In effect, the value of b (the bias term) in the equation for the PI controller has been changed to a new value; i.e., since e is 0, b takes on the value of the new controller output.

Application of the PI Controller

Process Heater Control System

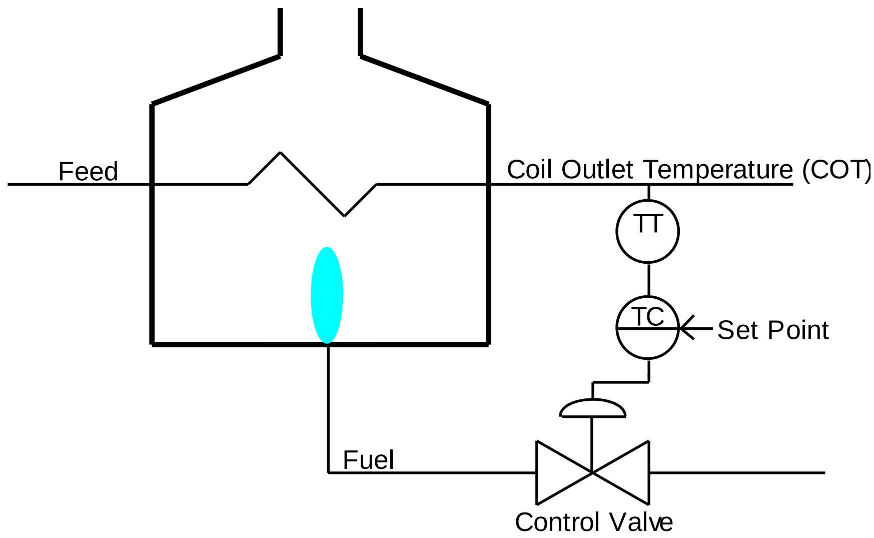


Fig. 4-2

Consider the example of the process heater (see Fig. 4-2). The control system (PI controller) is in automatic with the error 0 (controlled variable equals set point).

The set point is suddenly raised. This results in a positive error. Proportional action causes the output of the controller to suddenly change. In addition, the integral action also begins changing the output of the controller. The fuel gas valve opens more, forcing more fuel and thus more heat into the furnace. This acts to reduce the error. The reduced error results in a smaller contribution from the proportional action; however, the integral action continues to raise the output of the controller although the ramping rate will be decreasing.

Eventually the error will reach zero. At this point integral action is zero. However, depending upon the process dynamics as well as the settings of the controller, there may be enough energy already input to the process to raise the temperature above set point; that is, the lags in the process are still acting, and even though the actual error is zero the controlled variable has not reached steady-state.

This surplus of energy will cause the temperature to rise above the set point. The error will now be negative and the proportional and integral action will act to reduce the output of the controller.

The controlled variable may go through several of these oscillations before eventually coming to steady-state. The magnitude of these overshoots and undershoots, as well as their period of oscillations, is related to the process dynamics as well as the actual settings of the gain and integral time of the controller.
Finding the "right" settings for the controller is called "tuning" the controller.

You should note that even a pure proportional controller may cause certain processes to oscillate (as observed in Chapter 3); however, **the tendency for a process to oscillate is increased when integral action is used**.

Reset Windup

Another term associated with integral action is reset windup. This occurs in analog controllers when reset action forces the output of the controller to go to 100% or 0%. In an electronic analog controller, the integrating amplifier's capacitor continues to charge, eventually saturating the amplifier. If the error changes polarity, the output will not move from 100% (or 0%) until the amplifier first comes out of saturation. Thus, the error signal first has to bring the amplifier out of saturation before the actual output signal to the final control element starts to change. This can cause the process to become unstable. All analog PI controllers now have additional circuitry to prevent this saturation effect.

Reset windup can also occur in a digital controller. The integral term of the PID algorithm behaves in an analagous manner to the capacitor of the analog controller. With a digital PI controller, reset windup is prevented by sensing the output state of the PI controller and freezing the integration calculation using a program statement.

Proportional-Plus-Integral-Plus-Derivative (PID) Controller

Definition of Terms

derivative time - A term that multiplies the rate of change of error producing derivative action. For a ramping error, derivative time is the interval by which derivative (rate) action advances the effect of proportional control on the final control element.

phase shift - The time difference between the input and output signal or between any two synchronized signals, of a control unit, system, or circuit, usually expressed in degrees or radians

loop gain - The product of the gains of all the elements of the loop.

velocity feedback - Velocity feedback is a term used in servo-mechanisms and refers to a feedback of the rate of change of position where position is the process or controlled variable. In a process control system, velocity feedback is derivative action.

Requirements for Derivative Action

In the previous chapter you found that integral action can eliminate steady-state offset. However, if improperly used, integral can also destabilize the control loop.

Integral action tends to add a lagging phase shift to the loop. A lagging phase shift in a control system is the property whereby the output falls behind the input in time, where the input may be a sinusoidally changing disturbance or set point and the output is the process variable.
When the controlled variable lags the set point in phase (if the set point were changing sinusoidally) by **180 degrees** and if the loop gain (gain of the process times gain of the controller times gain of the sensor) is at least 1, then the process control system will become unstable (see Fig. 5-1). Of course, the input isn't generally varied sinusoidally; however, any noise in the system (noise contains many frequency components) could start the oscillations.

As integral adds a phase shift that lags, you can see that it contributes to the instability of the loop.

Derivative action adds a leading phase shift, which tends to subtract from the lagging phase shift caused by the integral action and the lagging phase shift in the process. For this reason derivative adds to the stability of the loop.

Conditions for Instability

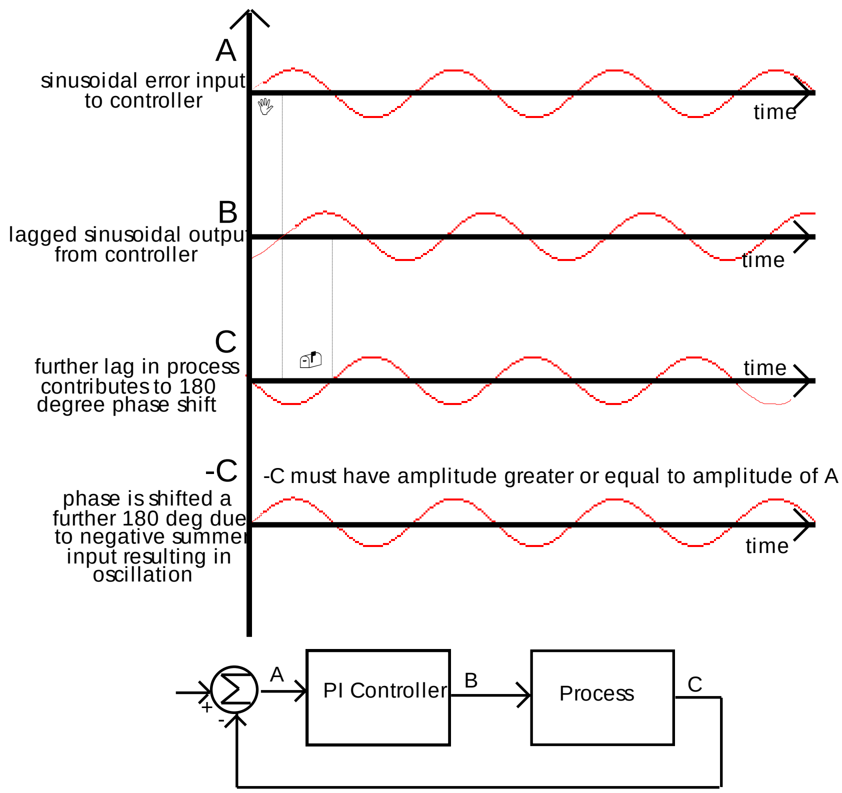


Fig. 5-1

To reduce large swings in controlled variable above and below the set point (overshoot), derivative action can be added to the controller.

Open-loop Response of the PID Controller

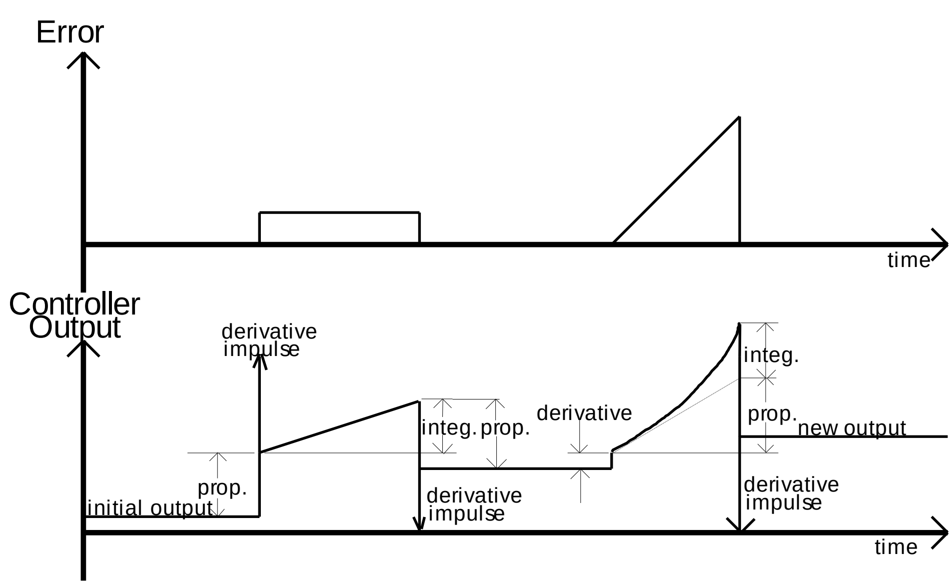


Fig. 5-2

Open-Loop Response for PID Controller

Mathematically, derivative action can be written as:

$$\text{Derivative} = K_c T_d \frac{de}{dt}$$

Thus, the output of the PID controller is:

$$C_{out} = K_c e + \frac{K_c}{T_i}\int e\,dt + K_c T_d \frac{de}{dt}$$

Where $\mathbf{K_C}$ is the controller gain
$\mathbf{T_i}$ is the integral time
$\mathbf{T_d}$ is the derivative time
e is the error

Derivative action (sometimes called rate or anticipatory action) acts to subtract from or add to the output from the controller, depending on the rate of change of error.

In the open-loop response shown in Fig. 5-2, you can see that derivative action adds a fixed value to the output of the controller only when the **rate of change of error** is a constant. At the points where the error makes step changes, the output of the controller generates a sharp pulse. The rate of change of the vertical edges of the error waveform are infinite.

Derivative Action

The important thing to remember is that the magnitude of the output from the **derivative element in the controller varies with the rate of change of error** rather than the error itself.

If you think of a system response that is oscillating but settling around a set point (see Fig. 5-3), you can see that at the point where the controlled variable is about to cross the set point the error is almost zero. It is at this point, however, that the rate of change of error is maximum.

Controlled variable Coming To Steady-state

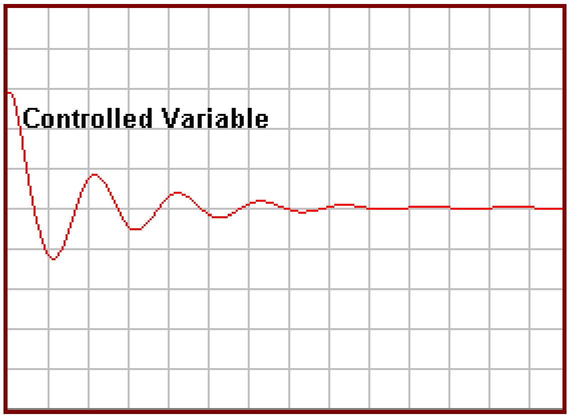


Fig. 5-3

Derivative action outputs a maximum signal at this "alignment" point to move the controller output in a direction that will minimize the overshoot. This action is similar to the damping effect of an automobile shock absorber.
In servomechanisms such as dc motor position control systems, this derivative action is called velocity feedback.

Because derivative responds to a rate of change of error rather than the magnitude of the error itself, it tends to be very sensitive to noisy processes (noise contains time-varying components with high rates of change). For this reason it should be avoided in processes that contain a great deal of noise (such as liquid flow).

In general, the additional overshoot caused by proportional-plus- integral action can be partially compensated for by derivative action.

For a given process, determining the "best" settings for the proportional, integral, and derivative settings is called "tuning the loop".

On many controllers equipped with derivative action, the derivative may be switch selectable to derivative of the controlled variable. Since the set point is constant in many applications, derivative on controlled variable is the same as derivative on error. However, derivative on controlled variable will not result in a controller output change when the set point is manipulated either by an operator or by another controller output such as in a cascade control system.

Tuning The Controller

Definition of Terms

reaction lag - Term used in Ziegler-Nichols open-loop method. This is the time between the start of the open-loop response curve and the intersection of a line that is tangential to the point of inflection of the response curve to a horizontal line, the vertical height of which is equal to the process variable before the step change. This concept is best illustrated in Fig. 6-5.

reaction rate - Term used in Ziegler-Nichols open-loop method. This is the slope of a line drawn tangentially to the point of inflection of the open-loop response curve. This concept is best illustrated in Fig. 6-5.

damped period of oscillation - The period of oscillation of the decaying or damped oscillatory response that may occur in a process control system after either a load disturbance or set point change is made.

ultimate period - Term used in the Ziegler-Nichols closed-loop response tuning method. When the integral and derivative actions have been turned off or minimized, the ultimate period is the period of the continuously oscillating wave that occurs after the proportional band has narrowed (gain increased) to a value where oscillation is sustained.

ultimate proportional band (P_{ult}) - Term used in the Ziegler-Nichols closed-loop response tuning method. This is the value of proportional band at which the ultimate period (see above) is measured.

self-tuning - A technique whereby the tuning constants for the PID controller are automatically calculated and downloaded into the PID controller. The tuning constants are usually obtained by measuring various characteristics of the controlled variable after small disturbances have occurred.

integrated absolute error (IAE) - A measure of controller error defined by the integral of the absolute value of a time-dependant error function; used in tuning automatic controllers to respond properly to process transients.

quarter amplitude decay (QAD) - A process control tuning criteria where the amplitude of the deviation (error) of the controlled variable, following a disturbance, is cyclic so that the amplitude of each wave is one quarter of the previous peak.

Criteria for Good Control

In most industrial processes it is important to ensure that the process control system responds in a manner to bring the controlled variable to steady-state (after set point changes and load disturbances) as quickly as possible. This generally involves some compromises. The process can be made to respond in a manner that the controlled variable reaches the set point very quickly with a consequent large overshoot as well as subsequent decaying oscillatory response. At the other extreme the process can be made to reach the set point very slowly with no overshoot at all. The manner in which the controlled variable responds to load disturbances and changes to set point can be dramatically altered by adjusting the proportional, integral, and derivative settings of the controller.

Generally, to measure the performance of the control system, calculate the integrated absolute error over time when a load disturbance or a set point change occurs. The objective of the control system would be to minimize this integrated absolute error (IAE), the total area between the steady-state value of the controlled variable and the oscillatory response (see Fig. 6-1). For a noisy controlled variable, the period of integration must be specified.

Integrated Absolute Error in Response of Controlled Variable

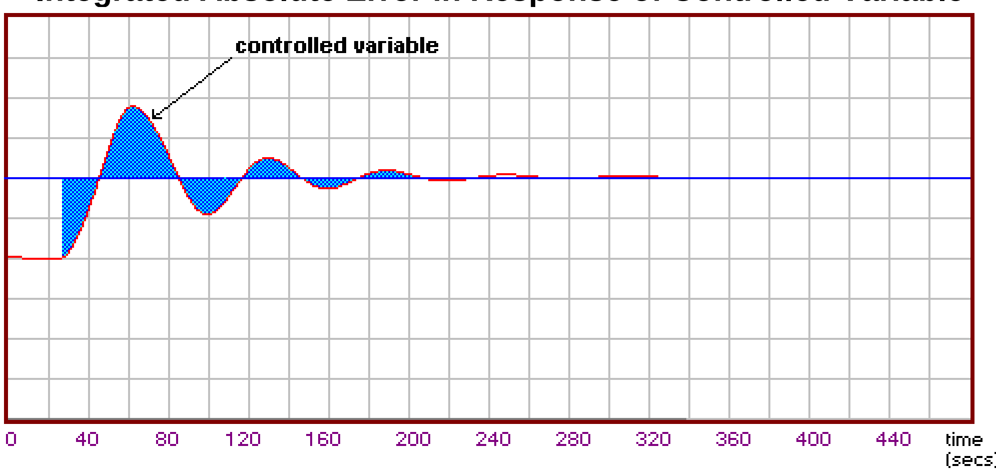


Fig. 6-1

Quarter amplitude decay or QAD is often used as a desired type of response of the controlled variable to set point and load disturbance changes (see Fig. 6-2). QAD means that the ratio of the second overshoot to the first overshoot is 1:4. QAD response is nearly identical to minimum IAE response.

QAD represents the response of a controlled variable that first reaches set point rapidly but settles relatively quickly after a set point change or load disturbance.

Quarter Amplitude Decay

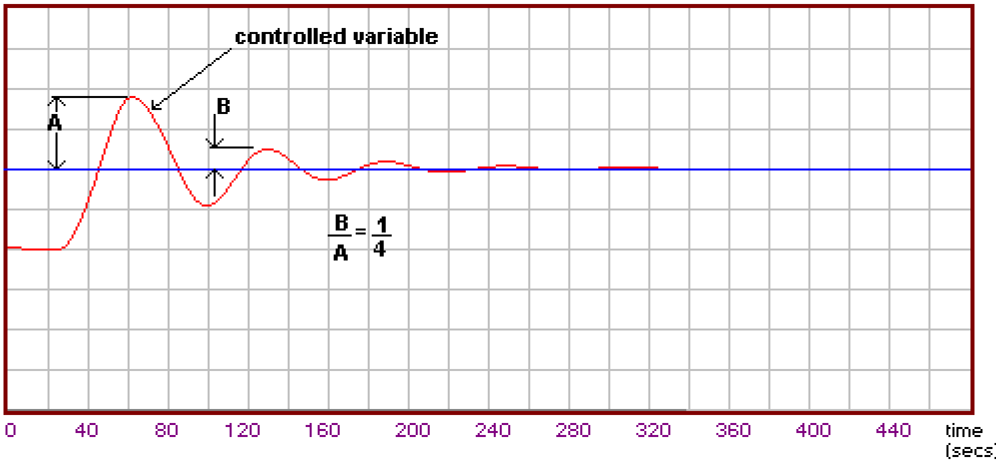


Fig. 6-2

In general the response that arises from a control system that produces QAD correlates well with minimizing the integrated absolute error.

It should be mentioned, however, that some processes cannot tolerate this type of response (large overshoot) and must be tuned for what is known as critical damping (critical damping is a controlled variable response that reaches the set point value as quickly as possible without overshoot). Utility plants, and robotic arms might be very different examples of processes that could not tolerate large overshoot due to QAD response.

For a set of tuning constants that produce QAD, an increase in the proportional band (reduction in controller gain) will result in a response that is more damped (exhibits less overshoot) but also results in a process that takes longer to first reach set point.

Tuning Methods

Experimental

Many individuals rely on experience to tune a given PID controller. Many techniques have been documented and have gone by various names including the "half-split", "cut and try", "damped oscillation", "binary division", "trial and error" and "feel" methods. Some of the methods place the process into continuous oscillation while others result in a damped oscillation. Generally, these approaches will involve steps similar to the following (the process may or may not be required to be placed into continuous oscillation):

(1) Set a wide proportional band (say, 300%).

(2) Set the integral time to a large value (say 100 min/rpt). This setting represents a small amount of integral action.

(3) Switch the derivative off (set to 0 sec).

(4) Decrease the PB initially by 20% of the actual value and introduce a small set point change (say, 2%). Repeat this process (alternating between positive and negative set point changes) until the process starts to continuously oscillate. Double the value of proportional band from the setting at which continuous oscillation first begins.

(5) Set the integral time to a value represented by 3/4 of the oscillation period in step (4). Decrease the integral value by increments of 20% of the actual value and introduce set point changes as in (4) until the process first starts continuous oscillation. Multiply the integral time at the point of oscillation by 3.

(6) Increase the derivative time in increments of 0.05 minutes, introducing set point changes as in **(4)**, until the process first continuously oscillates. Set the derivative to 1/3 of this value at which continuous oscillation begins.

The approach outlined above tends to give a controlled variable response that produces more damping than that for QAD (less overshoot).

Ziegler-Nichols Techniques

Ziegler and Nichols in the 1940's developed techniques whereby the characteristics of the process could be estimated using simple plant tests. From the results of these tests, they developed equations to determine optimum tuning constants. These techniques are still widely used today.

The Ziegler-Nichols closed-loop technique involves causing the closed-loop process control system to oscillate (see Fig. 6-3). This is done by setting the integral to maximum (10000 min/rpt) and turning the derivative off. The proportional band is then lowered until the controlled variable just begins to oscillate. The period of this oscillation is then measured, and from this the tuning constants are calculated using the equations:

$$PB = 1.67\ PB_{ult}$$
$$I_t = T_p/2$$
$$D_t = T_p/8$$

Ziegler-Nichols Closed-Loop Method

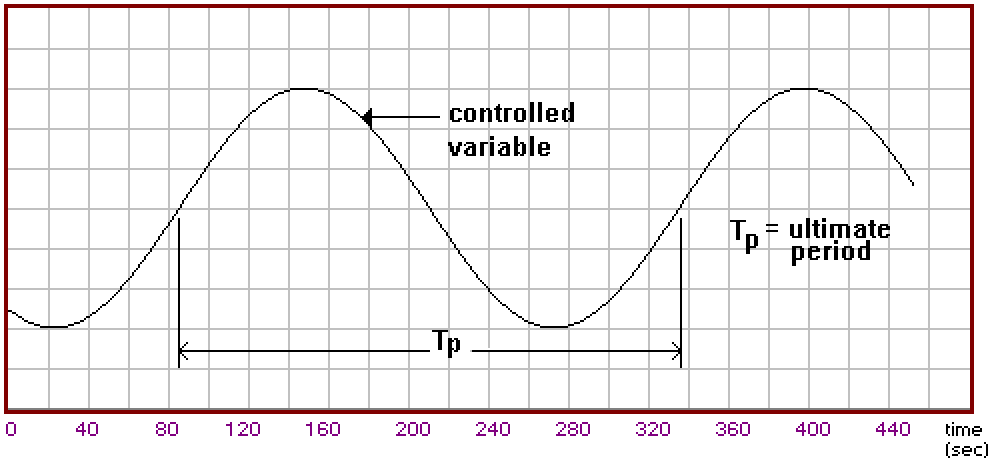


Fig. 6-3

The Ziegler-Nichols open-loop tuning technique (ZNOL) essentially approximates the step response (process reaction curve) for any process as one having single time constant with dead time. The values of time constants and dead time are then used to produce a set of tuning constants that will result in a set point response that approximates quarter amplitude decay. As these results are based on Ziegler-Nichols empirical findings, they yield approximations to quarter decay. Best results are obtained when the ratio of dead time to time constant is between 0.1 and 1.

Example of Ziegler-Nichols Open-Loop Technique

As an example, consider process heater (see Fig. 6-4).

Process Heater

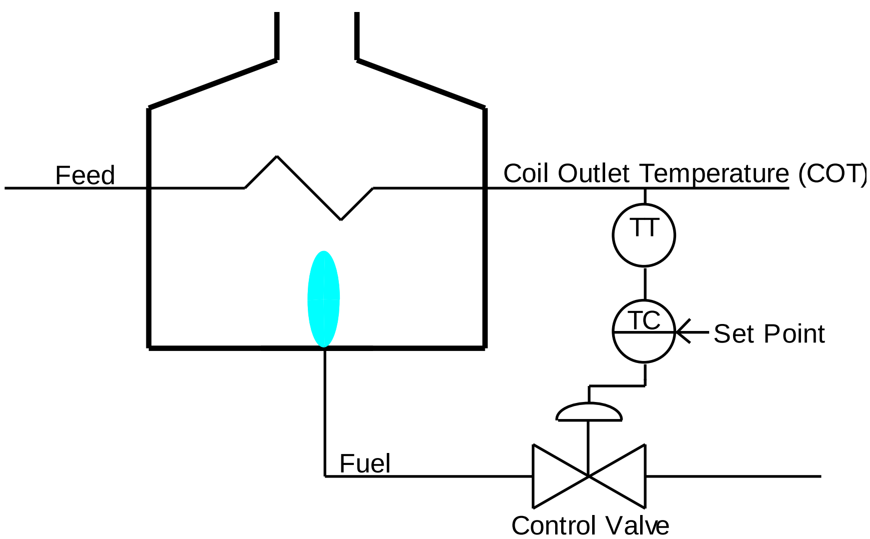


Fig. 6-4

In generating the process reaction curve in an industrial process, what is done generally is to place the controller in manual and make a very small (< 5%) step change in the manipulated variable. The recording device should be marked at the instant the step change is made. The curve is then obtained and the data retrieved.

In the furnace, after the coil outlet temperature has come to steady-state, the coil outlet temperature controller is put into manual. The manual controller output is then increased a small amount, putting more fuel gas into the furnace, and the process reaction curve is generated (see Fig. 6-4).

From the step response, the process characteristics are measured (the process is actually approximated as a single time constant process with dead time), and the tuning constants are calculated using the following equations:

$$PB = 83.3\ LR/M$$
$$I_t = 2.0L$$
$$D_t = 0.5L$$

Ziegler-Nichols Open-Loop Method

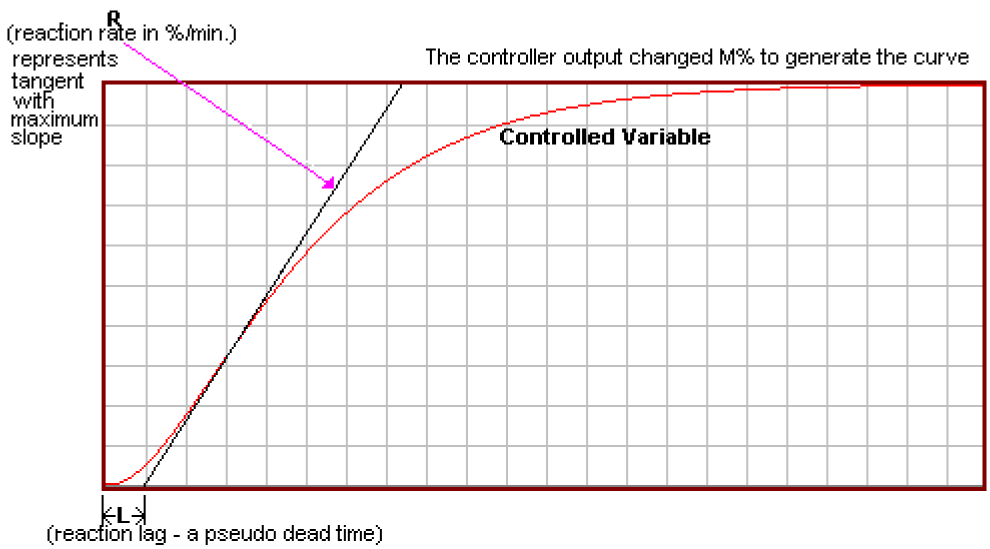


Fig. 6-5

Please note that these techniques produce an approximation to QAD. You should not be too concerned about the degree of accuracy in the QAD response. If the QAD produces a 4:1 ratio to within 20% accuracy, you should be satisfied that the settings on the controller are adequate.