1.0 INTRODUCTION

The SOLTEQ® **Level Process Control Module(Model: SE270-2)** consists of a liquid based process system design to study level control. The system exhibits realistic response times, uses standard industrial process instruments and process equipments.

The equipment is self contained and constructed on a bench top. The pump, tank and valves are strategically located for easy access. For safety reason, the control panel is protected against water splashes. The process piping is made of stainless steel material. Level tank is made of transparent glass for viewing purposes.

The control panel is connected to a SCADA system. Various parameters from controller could be accessed and controlled remotely thru a PC.

2.0 GENERAL DESCRIPTION

2.1 Process Description

The flow process control trainer is a water process. Water from sump tank, T-201 is pumped by P-201 to the level control tank T-201. The discharge from T-202 back to T-201 is by self regulatory mode. Tank level is measured via a level transmitter and is regulated by a control valve, LCV-201.

2.2 Unit Assembly and Instrument Description

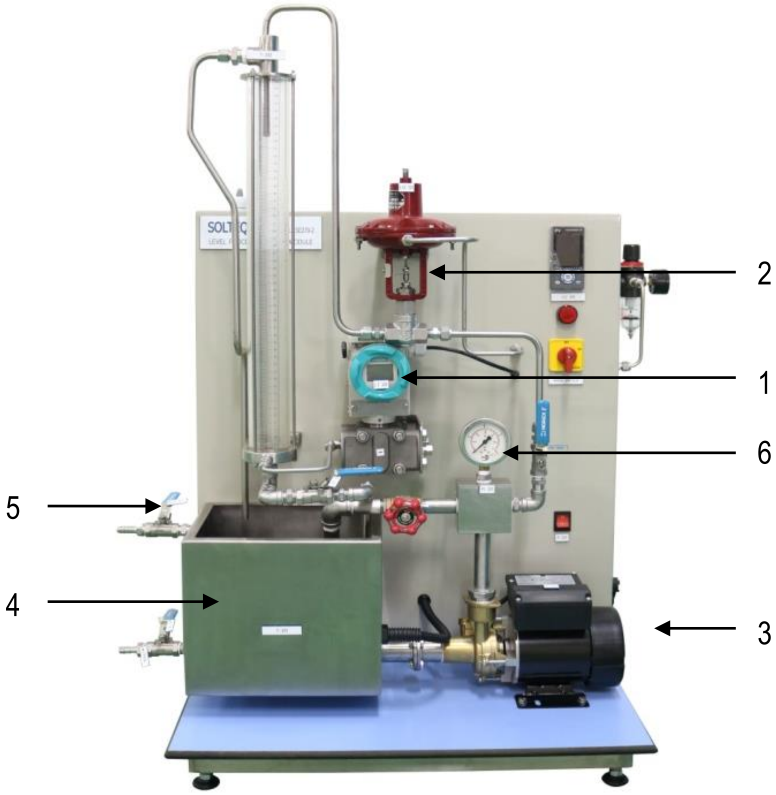


Figure 1 : *Instruments Construction for Level Process Control Module (Model: SE270-2)*

No.	Instrument	Tag No.	Description	Range
1	Level Transmitter	LT-201	Water flow transmitter giving 4–20mA output	0 – 100% (0–300mmH20)
2	Proportional Control Valve	LCV-201	1/4 inch globe valve with orifice Cv 0.32	0 – 100%
3	Process Pump	P-201	Water Circulation Pump	30 LPM
4	Process Tanks	T-201 T-202	Water Sump Tank Level Control Tank	10 L 0.5 L
5	Hand Valves	HV201-HV204	Input / Output isolation valves and load change	-
6	Pressure Gauge	PI-201	Line Pumping Pressure Monitoring	0-4 barg
7	Level Controller	LIC-201	Level PID Controller	0 – 100%

Table 1 : *Instruments Description for Level Process Control Module (Model: SE270-2)*

2.3 Specifications

a. Water Pump Tank
- Capacity : 10L
- Material : SS304
- Complete with level switch for pump safety pump off

b. Centrifugal Pump
- Max Flow : 30 LPM
- Max Head : 30M

c. Level Transmitter
- Range : 0-300mmH20

d. Control Valve
- Type : Globe
- Material : SS304
- Control Signal : 3...15psi

e. Level Control Tank
- Material : Glass

f. Microprocessor Controller
- Type : PID
- Input : 4...20mA
- Output : 4...20Ma
- Control : P,PI, and PID and Self-Tuning

2.4 Experimental Capabilities

- Demonstration of Proportional Control
- Demonstration of P + Integral Control
- Demonstration of PI+ Derivative Control
- PID Loop Tuning for Optimum Control

2.5 Overall Dimensions

- Height : 0.7 m
- Length : 0.6 m
- Depth : 0.22 m

2.6 General Requirement

- Water Supply : Laboratory tap water
- Pneumatic Air Supply : 10 LPM @ 30 psi
- Electricity : 220-240 V /1-phase /50 Hz

3.0 THEORETICAL BACKGROUND

3.1 Process Control

A fundamental component of any industrial process control system is the feedback control loop. It consists of a process, a measurement, a controller, and a final control element, as shown in Figure 2. If all these elements are interconnected, that is, if information can be passed continuously around the loop, this is closed-loop control and automatic feedback generally exists.

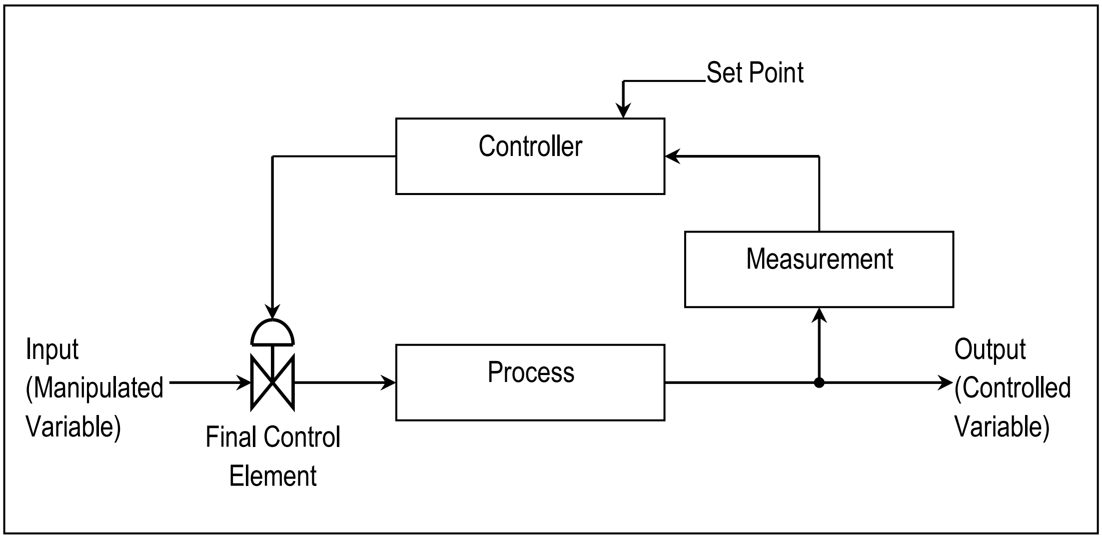


Figure 2: *A Closed Control Loop*

The information flow provides the means for control, which allows efficient utilization of raw materials and energy. If a loop is interrupted for any reason, such as when the controller is placed on manual control as shown in Figure 3, it is considered to be open-loop control and automatic control no longer exists.

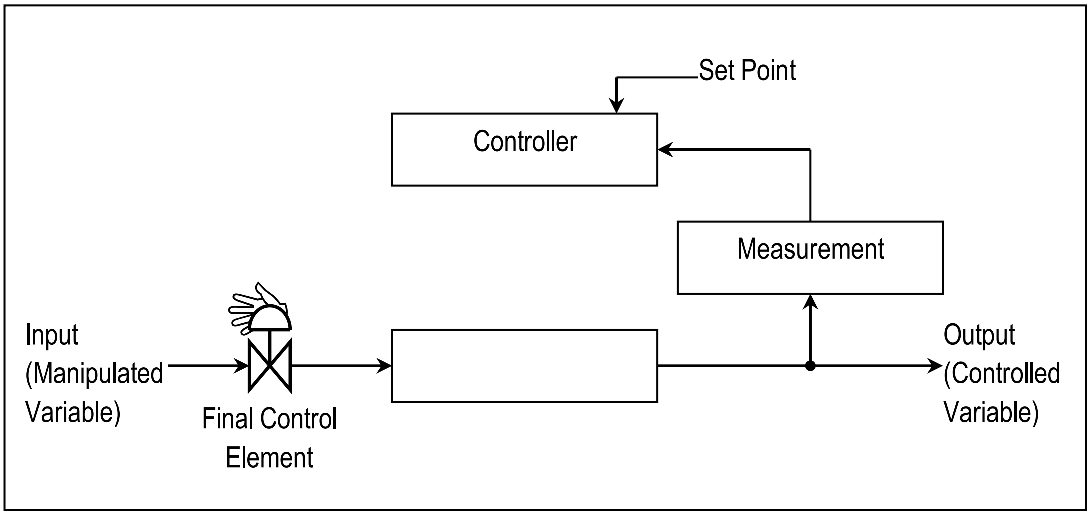


Figure 3*: An Open Control Loop*

The concept of automatic feedback control is not new. The first such industrial application occurred in 1774 when James Watt used a fly ball governor to control the speed of his steam engine. Understanding of automatic feedback control loops developed slowly at first. Pneumatic transmission systems did not become common until the 1940s, but past few decades have seen extensive study and development in the theory and application of those concepts.

Automatic feedback control is not used universally. In Figure 3 parts of the system are disconnected, creating open-loop control. Open-loop control does not feed information from the process back to the controller. A familiar example is the domestic washing machine, which may be programmed to control a series of operations necessary to wash a load of clothing. it runs through its cycle and, since no information is fed back to the control device regarding the condition of the wash, it shuts down. Only a human agent inspection the load, and finding it unsatisfactory, can institute corrective action. Open-loop control is seldom encountered in industrial processes and will be given no further consideration.

As stated before, automatic control requires some sort of signal system to close the loop and provide the means for information flow. This means that the controller must be able to move the valve, the valve must be able to affect the measurement, and the measurement signal must be reported to the controller. Without this feedback, you do not have automatic control.

3.2 On/Off Control

On/off control is generally both the simplest and the least expensive type of process control. This On/off control has wide application in industry. A process controlled by an on/off controller almost always has some error in it; in fact, the controller turns on or off only at those times there is no error in the measurement, when the measurement crosses the set point on its way from one extreme error to another. At that point, the valve goes either fully open (on) or closed (off), depending on the direction of the error. The size of the error is not recognized.

No attempt is made to balanced the inflow with the outflow; therefore. The energy or material supplied to the process is always either too much or not enough. The measured variable cycles continuously. However, when on/off control is applied to the right type of process, the effect of the cycling is small and acceptable.

On/off control best applied to a large capacity process that has relatively little dead time and a small mass or energy inflow with respect to the capacity of the system.

A common example would be a typical domestic heating system. A house gets colder than the desired temperature (set point) and the thermostat turns the heater on. The heater supplies enough heat to warm the house to the desired temperature, and the thermostat turns the heater off.

However, there is still enough heat stored in the mass of the house to keep it warm for a while. When the temperature returns to the set point, the thermostat turns the heater on again, but the temperature drops a little more before the heater starts to take effect and warm the house again (dead time).

This cycling is illustrated in Figure 4, which shows the relationship between the temperature of the house (the controlled variable) and the action of the heater (the manipulated variable). Because the mass of the house constitutes a large capacity, the variation in temperature caused by the cyclic effect is so small that it goes unnoticed by the people in the house.

In industry, a typical application for on/off control is the temperature of a large tank or bath. These also have large thermal capacities, with a small source of heat (the energy inflow) warming the liquid in them (the controlled variable) to the desired temperature (the set point).

In either example, the rate of rise (or fall) of the controlled variable is small because the energy inflow is small compared to the large capacity of the system.

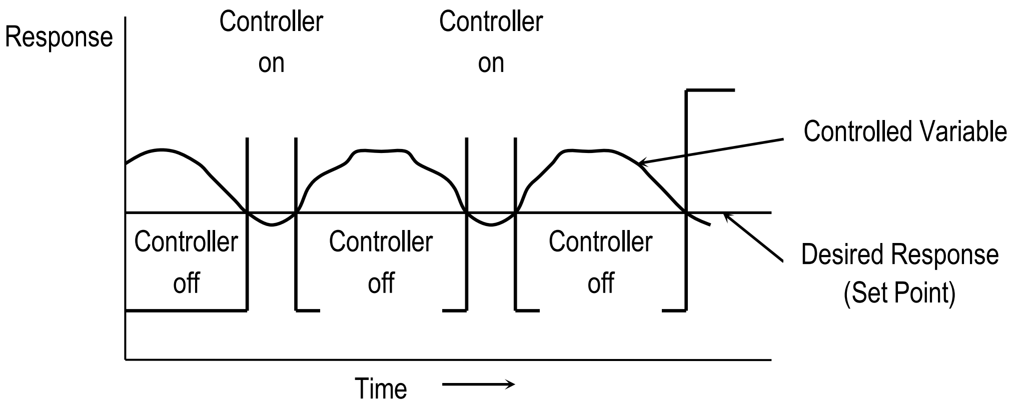


Figure 4*: System Response to a Process Upset with On/Off Control*

3.3 Proportional Control

On/off control works best on processes with large capacities that change slowly. When a process has small capacity, it usually responds quickly to upsets. Therefore, precise continuous regulation of the manipulated variable is needed. Proportional control attempts to stabilize the system and avoid fluctuations by responding to the magnitude as well as the direction of the error.

The type of process that benefits most from proportional control has a large mass or energy inflow with respect to the capacity and very little dead time.

A bathroom shower is an example of a small capacity process. On/off control of water temperature is useless here because turning the controls fully on or fully off causes too radical a change in output. The energy inflow is large with respect to the capacity of the process. So, we established a proportion of hot water to cold water that can be maintained continuously.

In the shower, as in most process control systems, the final control element is a valve that partially opens or closes to regulate the mass or energy inflow. To provide appropriate output, the valve travels between fully open and fully closed as positioned by the controller. This valve travel is called the valve stroke.

The relationship between the output and the width of the measurement span is called the proportional band. Sometimes called PB or PBand, it is expressed in percent. For example, a 20 percent proportional band is narrow; it provides sensitive control because 100 percent output change is produced by only 20 percent measurement change. Conversely, a 500 percent proportional band is very wide with only 20 percent of the possible output produced by 100 percent change in measurement.

In operation, the proportional controller calculates the amount of error between the measurement and set point, amplifies it, and positions the final control element to reduce the error. The magnitude of the corrective action is proportional to the error. Generally, the measurement proportional-only controller can completely eliminate offset at only one load condition.

When there is a process upset, such as when flow is suddenly reduced, the valve must change position to keep the controlled variable at a constant level (maintain the set point).

The output from the controller (which controls the valve position) must assume a new value, different from the original (the set point), before equilibrium can again be reached. This new value of the controlled variable is offset from the set point. Figure 5, Curve C, shows system response when the proportional band in which the oscillations settle out quickly.

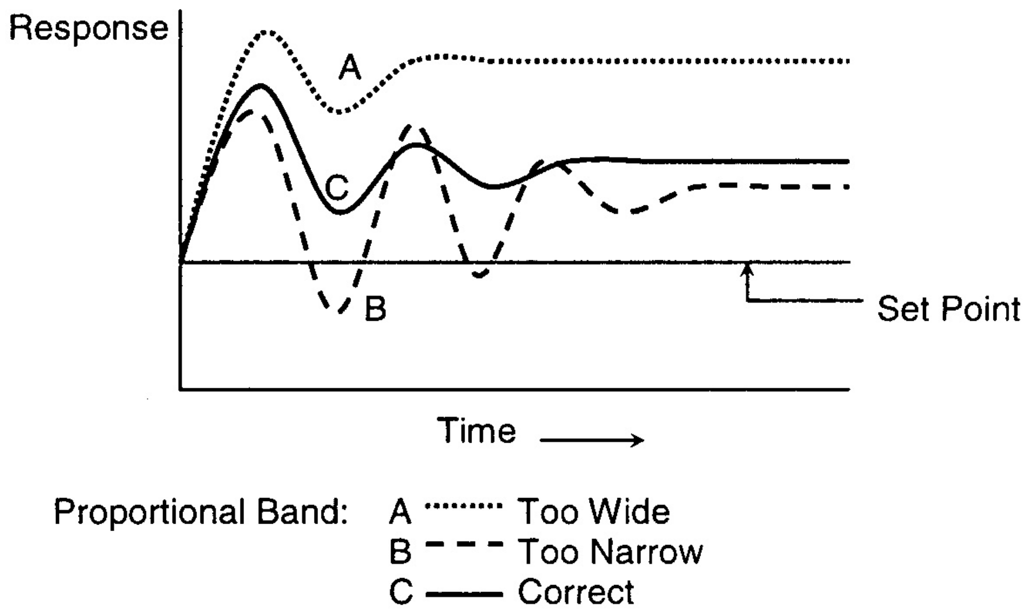


***Figure 5**: Proportional-Only System Response to a Process Upset with Different Proportional Band Widths*

If the proportional band is too wide (insensitive), the offset will be much larger, reducing the amount of control over the process. Narrowing the proportional band (increasing the gain) can reduce the amount of offset, but too narrow a band creates cycling. The most important limitation of proportional-only control is that it can accommodate only one fixed relationship between input and output, one control load where input error is zero and one output signal which positions the control valve in the position required to make the error zero.

Pure proportional action is generally adequate for a process that is stable using a narrow proportional band and where a small offset is not detrimental to the operation of the system. For example, non-critical temperature level control loops with long time constants are good applications for proportional-only control.

3.4 Integral Control

Integral action avoids the offset created in proportional only control by bringing the output back to the set point. It is an automatic rebalancing of the system that operates as long as an error exists. Therefore, integral control responds to the duration of the error as well as its magnitude and direction. Integral control is almost never used alone; rather, it is combined with proportional control.

At one time, the system rebalancing had to be done manually; this was called "manual reset." The term "reset" is occasionally still used, although a complete definition of the function includes the mathematical concept of integrating the error until it reaches zero.
Proportional-plus-integral (PI) control is generally used on processes where no amount of offset can be tolerated.

Other applications include those where such a wide proportional band would be required for stability that the amount of offset created would be unacceptable.

PI control is applied to almost all processes. The rare exceptions would be gas pressure control and non-critical liquid level control.

In a proportional-plus-integral controller, integral action can be expressed in terms of minutes per repeat—the amount of time necessary for the integral controller to repeat the open-loop response caused by the proportional mode for a step change in error. Smaller integral time value will yield faster integral action. (Some controller manufactures express integral action in repeats per minute, which is the reciprocal of minutes per repeat.)

Ideally, the minutes per repeat chosen for the integral mode of the controller should bring the control point back to the set point quickly. (The proportional band is specified separately.) If the integral time is too long, the system will not perform at maximum efficiency. If the time is too short, the measurement will overshoot the set point. In fact, if the integral time is too short for the process being controlled, a continuous cycle may result. Three relationships are shown in Figure 6.

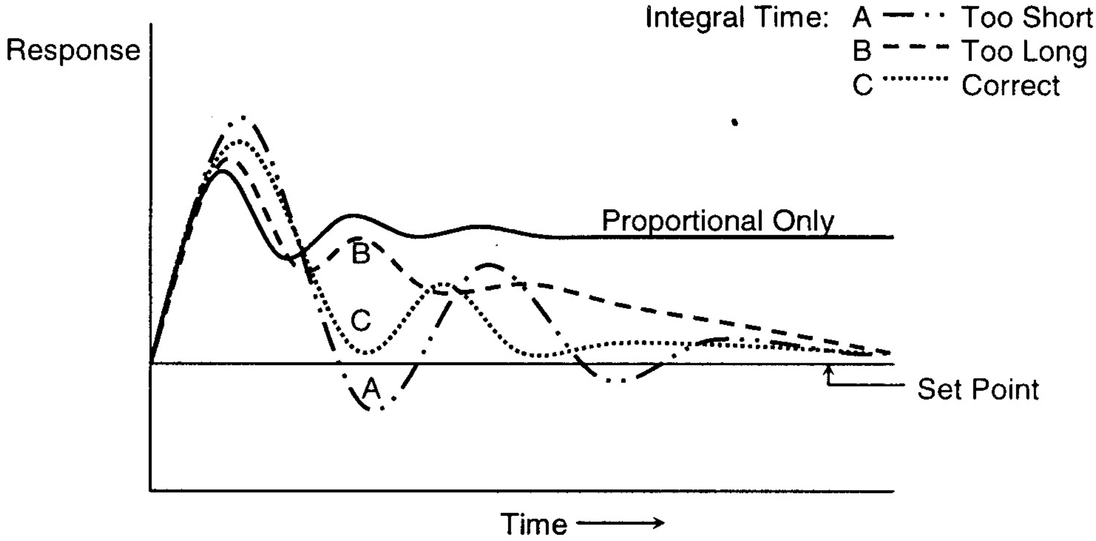


***Figure 6**: Proportional-Integral (PI) system response to a process upset with different Integral time*

One problem with integral control can occur when a deviation cannot be eliminated over a period of time (as with batch processes when a tank is empty). The controller continues to see an error and tries to correct for it, saturating the output to its maximum value. This is called integral windup. When the situation causing the error is corrected, the controller does not immediately return to normal operation; it holds the output—and the valve – at the extreme for a period of time after the deviation has reversed sign.

3.5 Derivative Control

Each of the basic control modes and the combinations discussed so far--proportional (P) and proportional-plus-integral (PI) have limitations. The limitations may not be significant if the process and controller are carefully matched.

However, some processes are so difficult to control or so critical to maintain at set point, that the use of all three modes will be helpful in achieving desired control. Derivative control responds to the rate of range of error. Hence, combined PID control responds to all aspects of process error—direction, magnitude, duration, and rate of change. The output of a PID controller is a linear combination of P, I, and D modes of control.

PID control can be advantageous on many processes. However, its application should be considered carefully because of its inherent limitations with some processes.

Processes that benefit most from PID control have rapid and large disturbances in which derivative action can respond to the rapidity of the changes, and integral action can respond to the duration of them.

Derivative and integral action are complementary. Derivative action permits an increase in proportional gain, offsetting the decrease necessitated by integral action. While integral action tends to increase the period of cycling of a loop, derivative action tends to reduce the period, thereby producing the same speed of response as with proportional action but without offset.

Temperature processes, such as the heat exchanger, is a typical applications that can benefit from PID control.

Figure 7 shows the effect of the addition of derivative action to a properly adjusted PI controller. The period (time to complete a cycle) is shorter than with proportional-plus-integral control.

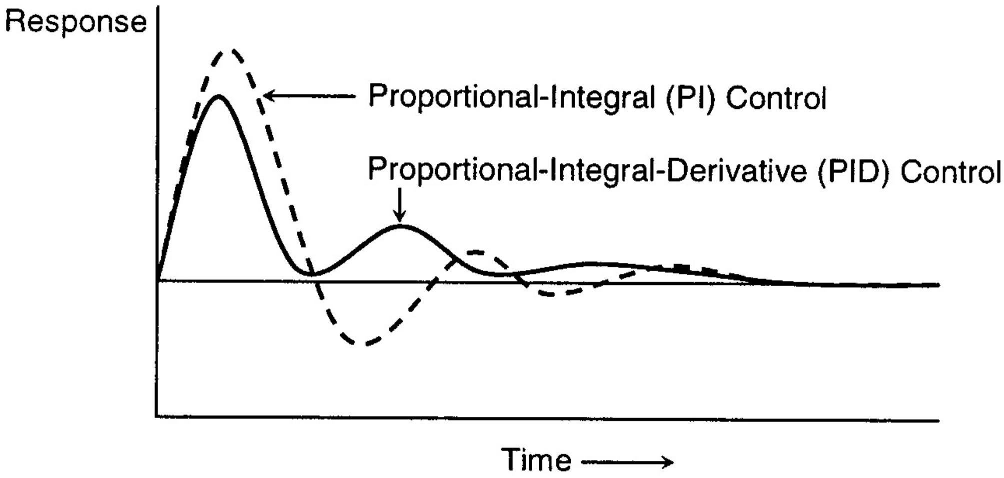


Figure 7*: Comparison of System Response to a Process Upset with PI Control and with PID Control*

Figure 8 shows the response of a system to a process upset in the primary analog control mode: proportional, integral, and PID. The uncontrolled response is shown for the sake of comparison.

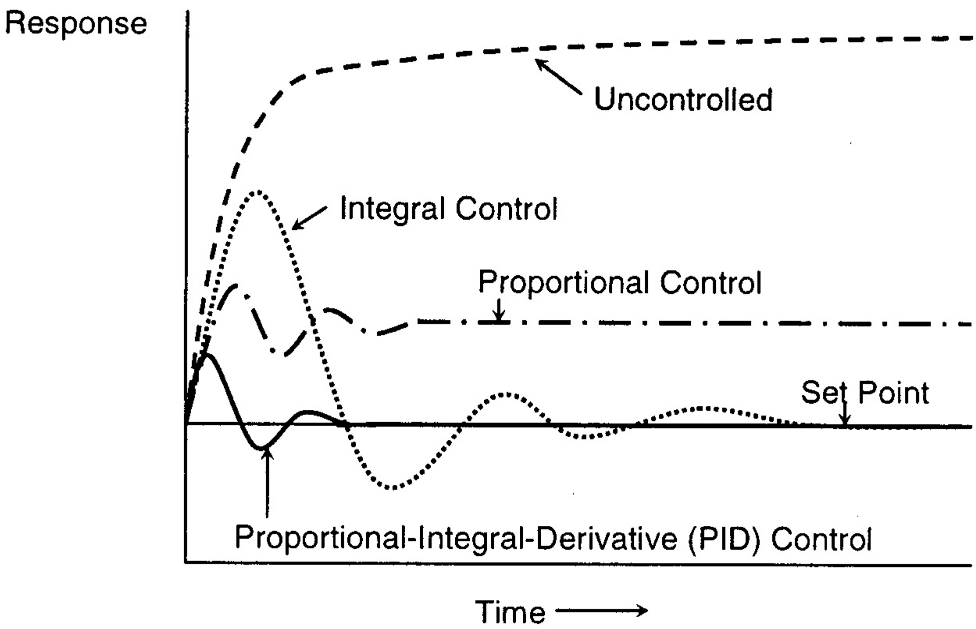


Figure 8*: System Response to a Process Upset with Different Modes of Analog Control*

Figure 9 shows the response of a system to a change in set point (as would happen in tuning a controller) using the same analog control modes.

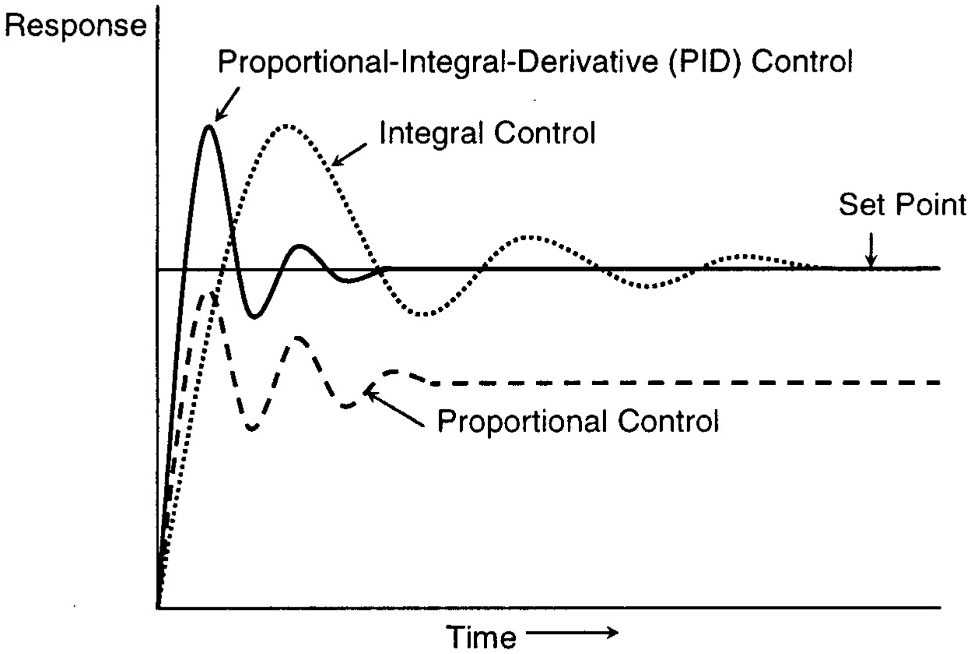


Figure 9: *System Response to a Change in Set Point with Different Modes of Analog Control*

3.6 Loop Tuning

The closed-loop control system attempts to achieve a balance between supply and demand by comparing the controlled variable to the set point and regulating the supply to an amount that will maintain the desired balance. Tuning the controller adjusts the supply so that balance is achieved as quickly as possible. This is done when the instrument is first put in service and, later, on a periodic basis as part of preventive maintenance.

When tuning, remember that each controller is part of a closed loop: all the parts of the loop are interactive, behavior of other devices in that loop. The controller response must be matched to that of the process. There are several procedures for doing this, some mathematical, most using trial and error.

A simple three-step method for tuning most three-mode controllers follows. (Batch controllers and one-through processes are special cases discussed after the three-mode and two-mode controllers.) This three-step procedure is based on a simple test to determine the nature period of oscillation of the process.

3.6.1 Trial and Error Method

Step 1: Set the integral time of the controller at its maximum and the derivative time at its minimum, thereby providing proportional-only control. Then reduce the proportional band until oscillation begins. Measure the period of this oscillation (also called the natural period) as the time between two successive crests or valleys (see Figure 10).

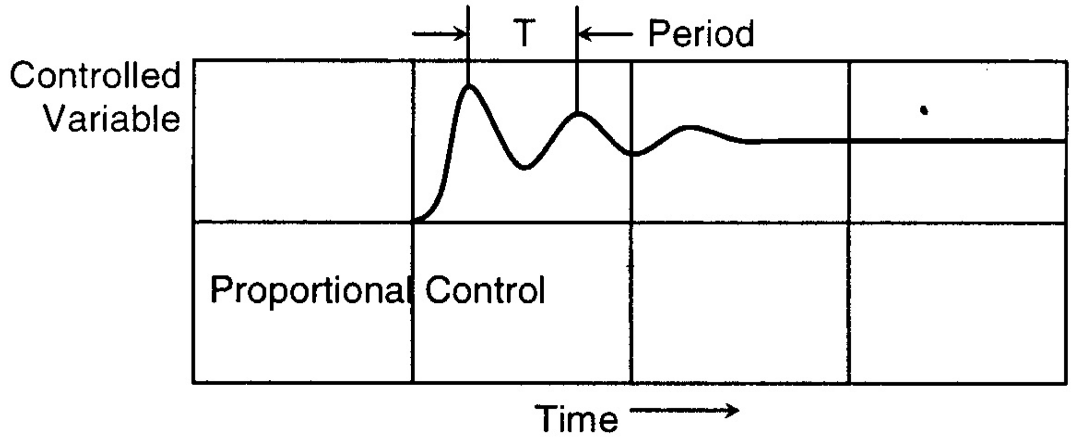


***Figure 10**: Period of Oscillation with Proportional-Only Controller after First Tuning Step*

Step 2: Set the derivative time at 0.15 times the natural period, and the integral time at 0.4 times the natural period. Observe the new period of oscillation; there should be a 25 percent decrease (see Figure 11). If the new period of oscillation is shorter than this, reduce the derivative time; if the period is longer, increase the integral time.

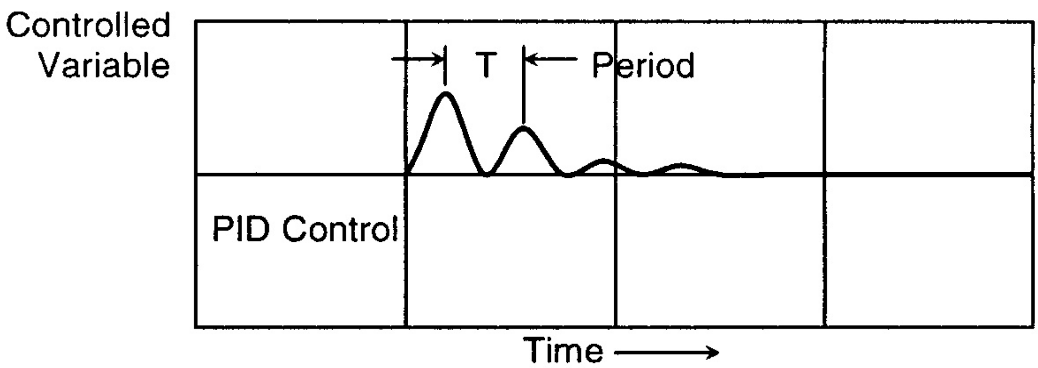


***Figure 11**: Period of Oscillation for Correctly Tuned PID Controller after Second Tuning Step*

Step 3: Finally, readjust the proportional band to achieve the desired degree of damping (the amount of correction to a process upset which, when too much or too little, shows up as either overshoot or sluggishness respectively).

When adjusting a two-mode (proportional-plus-integral) controller, a slightly different method should be used since integral mode introduces phase lag that is not counteracted by derivative. The procedure is as follows.

Step 1: Set the integral time of the two-mode controller at its maximum and the derivative time at its minimum, thereby providing proportional-only control, just as with the three-mode controller tuning. Then reduce the proportional band until oscillation begins and measure this period.

Step 2: Set the integral time to the natural period. The period of oscillation should increase about 40 percent (ideally, 43 percent). If the period is longer than this, increase the integral time (see Figure 12) and vice versa.

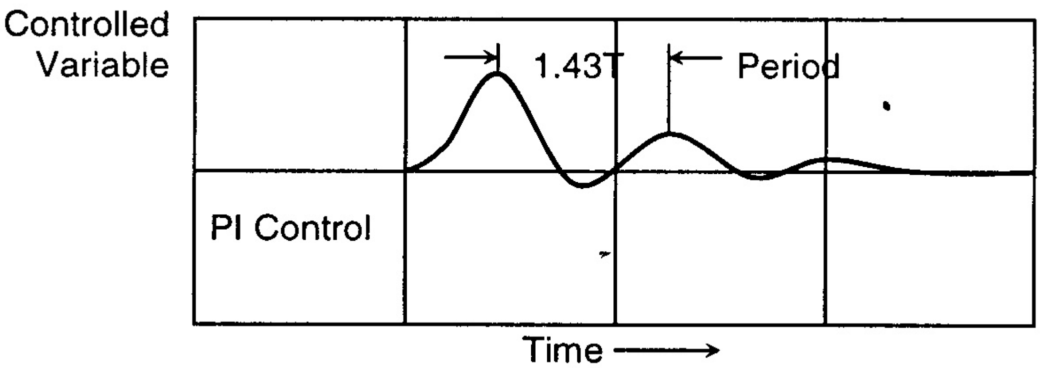


***Figure 12**: Period of Oscillation for Correctly Tuned PI Controller after Second Tuning Step*

Step 3: Finally, adjust the proportional band until the desired degree of damping is achieved. Adding integral control will always increase the proportional band required for stable control.

Some consideration must be given to processes with variable dynamic characteristics. Once-through processes such as tubular heat exchangers exhibit a natural period that varies inversely with flow. In such situations, one combination of controller settings cannot be ideal for all flow rates. Integral time should be set according to the lowest anticipated flow rate, and derivative time according to the highest.

Some batch controllers, because of their mechanical arrangement, will become unstable if equal values of integral and derivative time are used. Always keep their integral time at least twice the derivative time

3.6.2 Mathematical Method

To determine controller setting, two methods: open loop step response and closed loop cycling are used to measure their characteristic. The former will yield the capacitance, τ_I, and dead time, τ_{DT}; the latter, the natural period, τ_o. However, we will just discuss about the closed loop method in this manual.

3.6.2.1 Open Loop Method

To determine capacitance and dead time via open loop response (also known as the reaction method), a recording device having a fast chart speed (say, ¾ in/min) is connected to the measurement signal. The test is then performed by:

1. Placing the recorder in the high speed mode, with the controller in the manual position and then measurement lined-out at a constant value.
2. Making a step change to the controller's output at some fixed value, such as 5 to 10%; and, at the same time, making a mark on the recorder chart so that dead time can be determined.
3. Removing he chart from the recorder when the measurement has reached a final value.

A typical response from a process having dead time and first order lag is shown in Figure 13. The elapsed time from the point where the step change was made until the measurement begins to rise is the dead time. It can be calculated by measuring the distance (in.) on the chart and driving it by the chart speed (in./min).

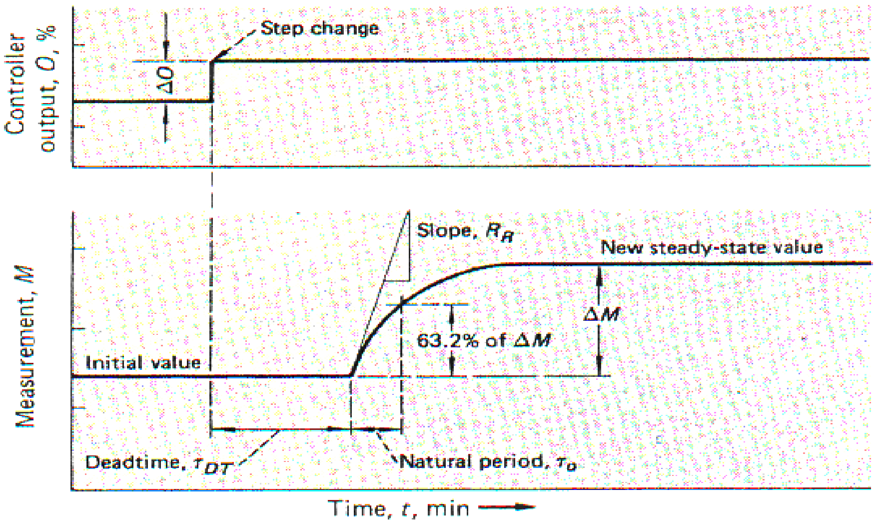


***Figure 13**: Open-loop response is typical of a process with dead time and lag*

The measurement (Figure 13) rises to a final value that is the new steady state, which results from the step change made in controller output. From this curve (approximating a response having a first-order lag for a single capacitance system), the time constant, dead time, and the process response rate or slope of the control loop can be measured.

The units of measurement for calculating the slope are the controller settings, usually expressed as percent or time. The slope of the response curve should be in units of percent/time, and is expressed as:

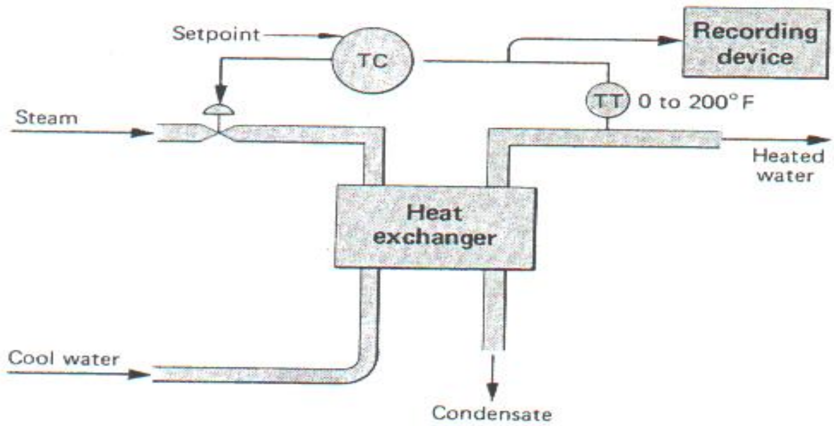
$$R_R = \frac{\Delta M / t}{\Delta O} \qquad (1)$$

Where,

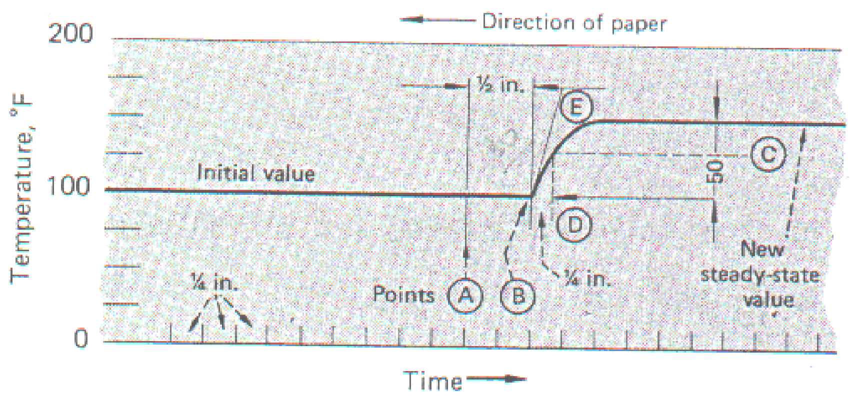
R_R = response rate, 1/min
ΔM = the change in measurement, %
t = time, min
ΔO = is the change in output, %

The controller settings for obtaining a specific closed loop response can be predicted from the results of this method by using algorithms developed by Ziegler and Nichols, Cohen and Coon, Shinskey, et al.

As an example of the open loop method, let us consider temperature control of the heat exchanger process shown in Figure 14a. Assume that the temperature of the water leaving the exchanger is 100⁰F, the temperature transmitter has a span ranging from 0 to 200⁰F, and the steam pressure remains constant. A chart recorder is attached to the measurement signal. The measurement before and after the step change would appear on the recorder as shown in Figure 14b.



a.Process



b.Chart recorder

Figure 14: *Temperature control for a heat exchanger process is analyzed via open-loop method*

For this example, the recorder has a chart speed of ¾ in/min. At Point A (Figure 14b), a step change of +20% is made to the output of the controller, and at the same time a mark for the measurement signal is made on the chart. At point B, the measurement begins to rise, and reaches a final value of 150⁰F. This temperature increase corresponds to the increase in steam flow. The chart travel through the recorder (after the step change is made and before the measurement rises) is ½ in. Since the chart moves at ¾ in./min; the dead time is calculated from

$$\tau_{DT} = 0.5/0.75 = 2/3\min = 40s$$

The next step is to locate the point at which 63.2% of the rise between the initial and final measurements occurs. This corresponds to a temperature of 131.6^{0}F. At this temperature, draw a horizontal line on the chart to intersect the measurement curve at Point C. Next, drop down to the line extended from the initial measurement to locate Point D. Measure the distance between Points B and D (which is ¼ in.). Then, the time constant for capacitance is calculated as:

$$\tau_I = 0.25/0.75 = 0.33\min$$

The final step is to draw a tangent to the maximum rate of rise, and to measure the slope of this line to find the response rate. The slope is determined as follows:

Y-axis: $\dfrac{50^o F}{200^o F} = 25\%$ change in input

X-axis: $\dfrac{0.25}{0.75} = 0.33\min$

Since the slope is proportional to the size of the output step, the units must be normalized before the slope is computed. Hence the response rate, R_R, becomes:

$$R_R = \frac{25\%/0.33\min}{20\% output} = 3.7/\min$$

3.6.2.2 Closed Loop Cycling

The closed loop cycling method is popular because only one parameter is measured. Its disadvantage is that some online process cannot be allowed to cycle for even a short period of time. By causing a control loop to cycle at a constant amplitude and period, its natural period, τ_o, can be determined. An example of a measurement that is cycling sinusoidally is shown in Figure 15.

To induce constant amplitude cycling in a process control loop, it is necessary to:

1. Make sure that the loop is in a stable condition.
2. Adjust the integral (I) and/or derivative (D) modes to minimum action if the controller has more than one mode (i.e., proportional plus integral, or proportional plus integral derivative).
3. Make a step change in the controller's set point, and observe the resulting measurement cycle.

4. Reduce the proportional band further if the measurement cycle damps out to a steady-state value, and, following this, make another change in the controller's set point.
5. Continue repeating Steps 3 and 4 until the measurement cycles at a constant amplitude and period, as shown in Figure 15. Also, be certain that the final actuator is not oscillating between its limits, because such oscillation will yield erroneous results.
6. Measure the peak-to-peak distance from the recorder's output of the measurement. Convert this measurement to time by dividing it by the speed of the chart in the recording device.

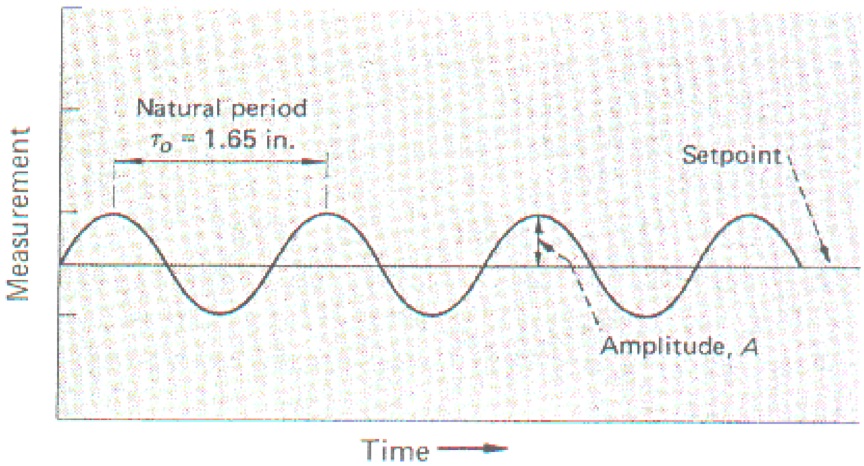


Figure 15: *Constant amplitude cycling is typical for the closed-loop method*

As an example of this procedure, consider the heat exchanger and control loop in Figure 14a. The temperature controller (TC) was switched to the automatic mode, and the proportional band reduced until the measurement cycled continuously, as represented in Figure 15. The peak-to-peak distance is measurement as 1.65 in. Therefore, the natural period for this cycling becomes:

$$\tau_o = \frac{1.65in.}{0.75in./\min} = 2.2\min$$

The proportional band that produced the cycling was 140%, and will be referred to as (PB)*, i.e., (PB)*=140%.

3.6.3 Errors in Measurement

A chart recorder or trending device may be used to track the response of the measured variable for the corresponding change in controller output. Since the controller settings are based on measurements from the recording element, any errors in recording and measuring are passed directly to those settings.

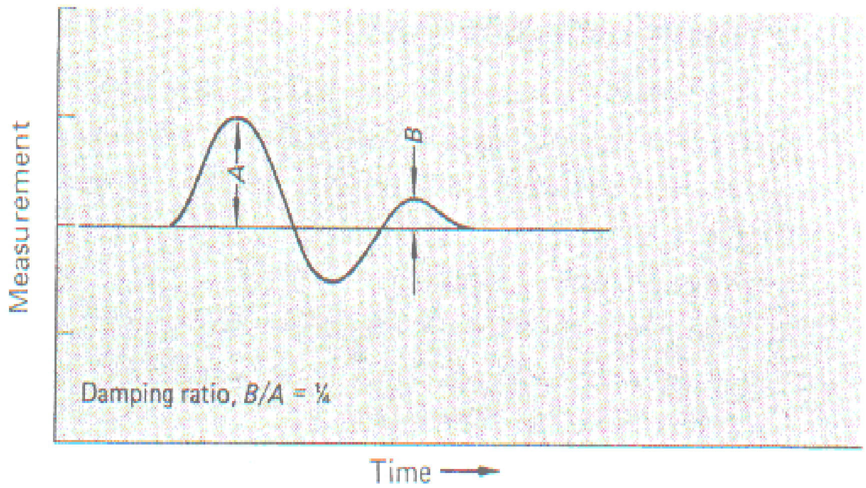
In addition, adjustments on the controller frequently have a resolution no better than 15% of the value indicated, because the adjustment dials have large graduations. Hence, one cannot expect an accuracy of better than +15% of the value desired for mechanical dials. Digital controller, on the errors arising from the overall system used to capture the responses need be considered in using digital controllers.

3.7 Tuning Objectives

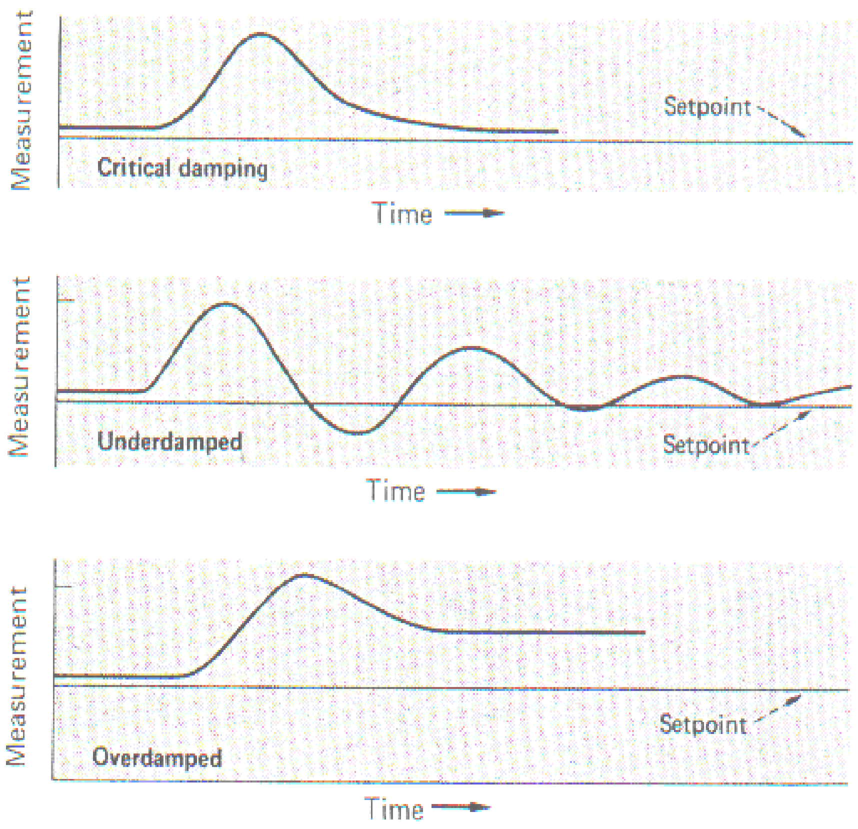
After measuring the natural period and/or the dead-time and capacity time-constant, controlled, controller settings can be determined by using relationships developed by Ziegler and Nichols, Cohen and Coon, Shinskey, and others. The objective of these investigators was to determine settings that would minimize the integrated error over time.

The methods for deriving such relationship are highly analytical and, therefore, difficult to use. In general, the response that results from an optimally tuned controller will be that of quarter-amplitude damping (*QAD*). Figure 16a is characteristic of *QAD*. This type of response correlates well with the minimized-error response, and is practical to use.

Some process cannot tolerate an oscillation about the final value, and so another type of response must be chosen. An example of a response curve for a proportional-only controller, approaching the final value, is shown by the curve in Figure 16b, and is called a "critically damped" response. If gain were added to this controller, the response path would cross the final value of the measurement more than once. A critically damped controller response will produce a larger total error than *QAD* but may be acceptable, depending on the particular process requirements.



a. Quarter amplitude damping



b. Effects of proportional band

Figure 16: *How fast a Loop stabilizes to an upset depends on Proportional Band*

If the gain of the controller is increased further, prolonged cycling will occur from an upset. This type of response is referred to as “underdamped”, and results in a smaller deviation from the set point (see curve in Figure 16b). Conversely, if the gain is reduced, the response to an upset will be reduced, resulting in a large deviation from set point (see curve), and a response referred to as “over-damped.

The formulas developed by Ziegler and Nichols for predicting controller settings to produce *QAD* are based on a process model having a capacity that is purely integrating. In the example of Figure 17, the level in the tank corresponds to the integrated value of flow. If a change in inflow occurs and the outflow remains constant, the tank will either empty or overflow. The steady-state gain, G_{SS}, of this process is infinity, and the process is said to be non-self regulating.

If the outflow from the tank is affected by changes in the inflow, the level in the tank will likely reach a steady state if the inflow upset is not too large. This type of process response is said to be self regulating. Cohen and Coon developed relationship for predicting controller settings to account for self regulation.

However, it is recommended that the Ziegler and Nichols relationship be used rather than those of Cohen and Coon, unless the ratio for τ_{DT}/τ_I becomes greater than 0.1.

Procedures and guidelines for tuning the common combinations of proportional, integral and derivative modes, along with criteria for their evaluation, will follow. The analysis of selected settings is required to compensate for errors in measurement and adjustment. In this respect, the procedures may be considered as an iterative approach.

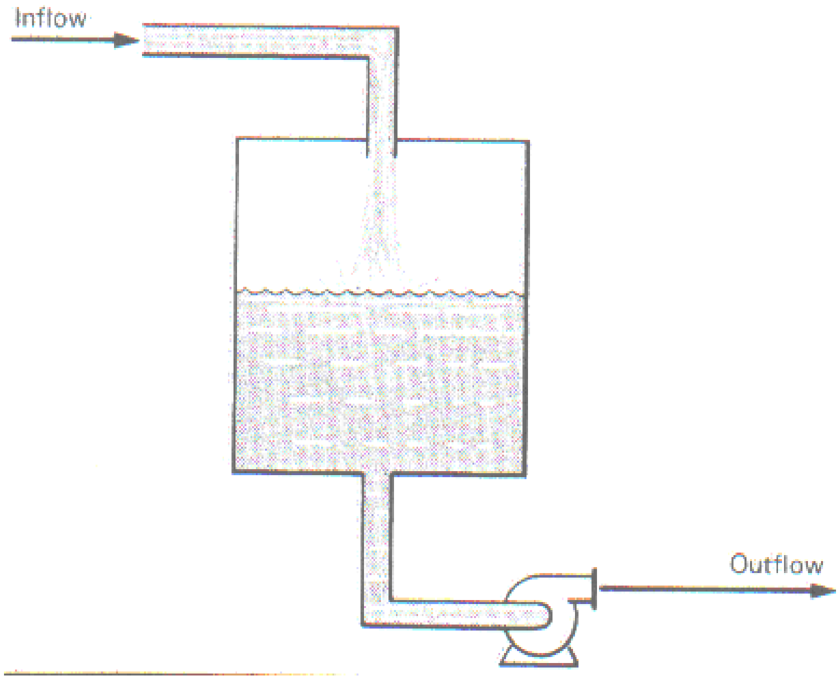


Figure 17: *Outflow is not affected by level in tank*

3.7.1 Proportional-only-Mode

The proportional-only controller finds application in processes that require a fast response and that, at the same time, can tolerate a constant deviation from the set point. The amount of this deviation is a function of proportional band and bias.

The proportional-only controller has one adjustment for tuning. Therefore, *QAD* is an acceptable criterion. The recommended settings are:

Method: Ziegler and Nichols, and Shinskey

Closed loop:

PB=2(PB)* (2)

where (PB)* is the proportional-band setting that produces constant-amplitude cycling

Open loop:

$$\frac{100}{PB} = \frac{1}{\tau_{DT} R_R} \quad (3)$$

Method: Cohen and Coon

$$\frac{100}{PB} = \frac{\left(1+\frac{\mu}{3}\right)}{\tau_{DT} R_R} \qquad (4)$$

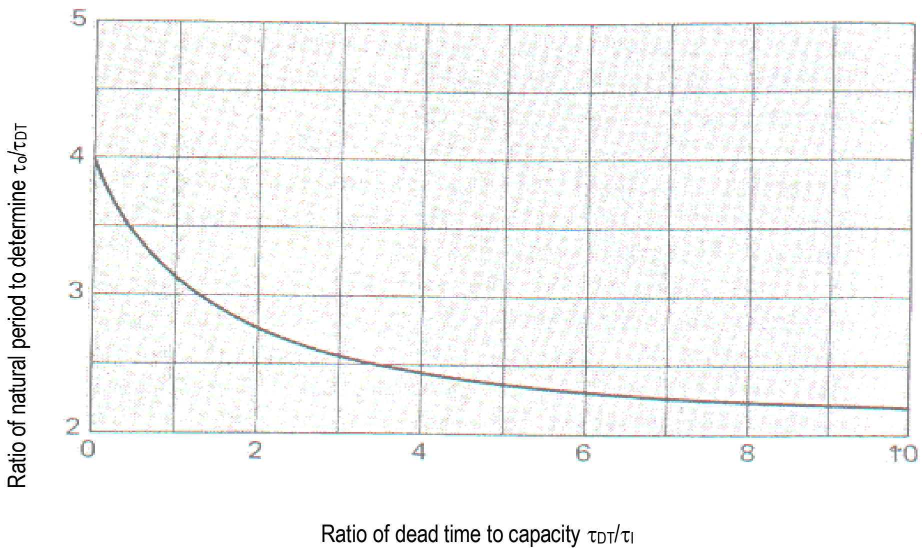
where $\mu = \tau_{DT} / \tau_I$

If *QAD* is not desired, an increase in the proportional band will result in critical damping; a further increase will produce overdamping. Decreasing the proportional band from the *QAD* setting will create underdamping.

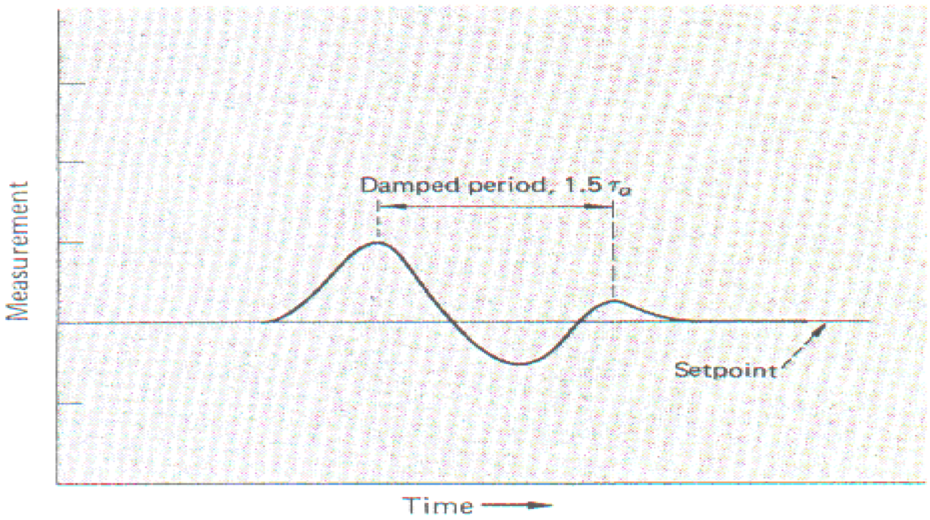
3.7.2 Proportional-plus-Integral Mode

The proportional-plus-integral (PI) controller is probably the one most often encountered. Its advantage is fast response and zero deviation from the set point at steady state. The tuning procedure for a PI controller is somewhat more difficult to evaluate because two adjustments exist, and many combinations of these will produce *QAD*. Therefore, other criteria are necessary to evaluate the predicted controller settings.

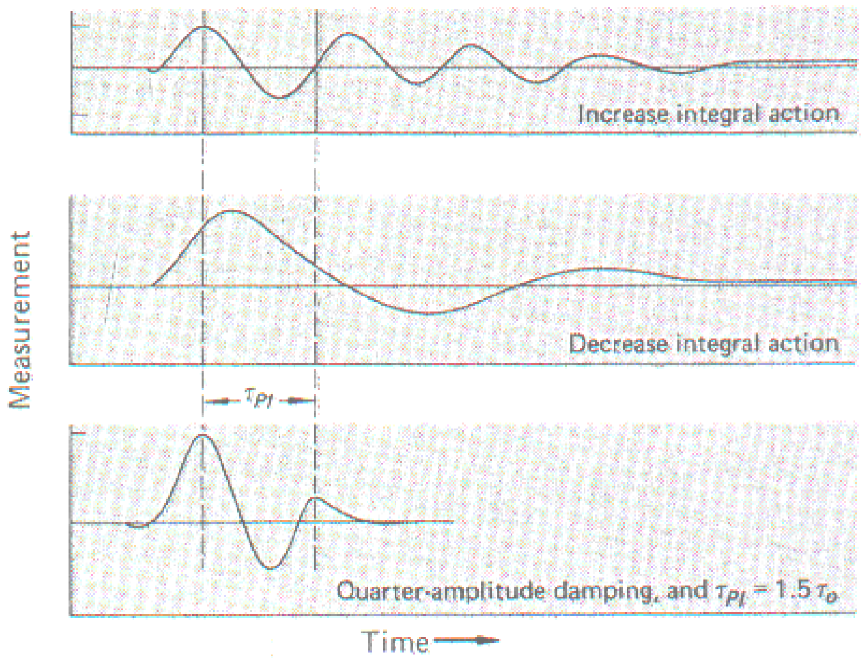
Shinskey has shown that the damped period of a properly tuned PI controller will be approximately $1.5\tau_o$. For processes in which the natural period, τ_o is difficult to determine, the value for τ_I and τ_{DT} can be determined by the open-loop method; and the natural frequency, τ_o, approximated from Figure 18a.



a. Chart for natural period, τ_o



b. Quarter-amplitude damping



c. Responses

Figure 18: *The natural period can be approximated for tuning a proportional-plus-integral controller, and the response to change in integral action evaluated*

The response of a PI controlled having a period equal to 1.5τ_o, and for *QAD*, is shown in Figure 18b. By increasing the integral action (Figure 18c) in controller, the damped period will increase, and oscillation about the final value will be longer. (The damped period of a proportional-plus-integral controller will be referred to as τ_{PI}, and equals 1.5τ_o). Decreasing the integral action will produce a response that will take longer to return to the set point.

The recommended settings based on the measurement of τ_o or τ_I and τ_{DT} or both are:

Method: Ziegler and Nichols

Closed loop:

PB=2(PB)* (5a)

$I=\tau_o/1.2$ (5b)

where I is the reset time, min.

Open loop:

$$\frac{100}{PB}=\frac{0.9}{\tau_{DT}R_R} \quad (6a)$$

$I = 3.33\tau_{DT}$ (6b)

Method: Cohen and Coon

$$\frac{100}{PB}=\frac{\left(1+\frac{\mu}{11}\right)}{\tau_{DT}R_R} \quad (7a)$$

$$I=3.33\tau_{DT}\left[\frac{\left(1+\frac{\mu}{11}\right)}{\left(1+\frac{11\mu}{5}\right)}\right] \quad (7b)$$

Method: Shinskey

PB = 2(PB)* (8a)

$I = 0.43\tau_o$ (8b)

Using the example of the heat exchanger (Figure 14) and the results from the open-loop and closed-loop tests, the settings will be determined by each of these methods for a proportional-plus-integral controller where τ_{DT}=0.67 min, τ_o=2.2 min, τ_I=0.33 min, R_R=3.7/min, and (PB)*=140%.

Using the Ziegler and Nichols relationships, Eq (5) and (6), the proportional band, PB and reset time, I for closed-loop and open-loop responses are calculated as:

Closed loop:

PB = 2(PB)* = 2(140) = 280%

$I = \tau_o/1.2 = 1.83$ min

Open loop:

$$\frac{100}{PB}=\frac{0.9}{R_R\tau_{DT}}=\frac{0.9}{(3.7)(0.67)}=0.363$$

PB = 275%

I = 3.33 τ_{DT} = 2.23min

Using the relationship of Eq. (7) yields:

$$\frac{100}{PB}=\frac{0.9\left(1+\frac{\mu}{11}\right)}{\left(\tau_{DT}R_R\right)}=\frac{0.9(1+0.18)}{0.67(3.7)}=0.428$$

PB=233%

$$I=3.3\tau_{DT}\left[\frac{\left(1+\frac{\mu}{11}\right)}{\left(1+\frac{11\mu}{5}\right)}\right]=3.3(0.67)(\frac{1.18}{5.4})=0.48\,\text{min}$$

Substituting into Eq. (8) produces:

PB = 2(PB)* = 2(140) = 280%

I = 0.43τ_o = 0.43(2.2) = 0.95 min

The predicted Cohen-Coon setting results in a higher controlled gain [where G = 100/PB], because their equations contain a factor to account for self regulation. The Ziegler and Nichols methods make no provision for this characteristic. Settings predicted by the Shinskey method result from a slightly different error-analysis approach, and are close to those of Ziegler and Nichols for the closed-loop test. Errors in measurement between the open-loop and closed-loop tests contribute to slightly different predicted settings.

3.7.3 Proportional, Integral and Derivatives Modes

The three-mode (PID) controller cannot be used on a noisy measurement, or on one that changes stepwise, because the derivative contribution is based on the measurement rate-of-change.

The PID controller is used on processes that are slow to respond and have long periods. Temperature control is a common application where the heat rate may have to change rapidly when the temperature measurement begins to change. Derivative action shortens response periods to an upset.

Due to the physical construction of most controllers, an interaction occurs between the integral and derivative modes. This interaction causes the effective values of the modes to differ from their set values. The effective integral time, $I_{t(eff.)}$, is actually the sum of two time constants:

$$I_{t(ff.)}=I_t+D_t \qquad (9)$$

The effective derivative time, $D_{t(eff.)}$,is:

$$D_{t(eff.)} = \frac{1}{\frac{1}{I_t} + \frac{1}{D_t}} \qquad (10)$$

Two important points concerning Eq. (9) and (10) are:
The effective value for derivative time can never be greater than one-fourth the effective integral time, which occurs when $D_t = I_t$.

1. When D_t is larger than I_t, the contribution to each control action is reversed. In other words, when setting D_t greater than I_t this changes the value for I_t more than for $D_{t(eff.)}$.

The rule-of-thumb is to never adjust a controller so that derivative action is greater than integral action.

The performance criteria for a PID controlled can be evaluated by measuring the damped period. Optimum tuning generally results with a *QAD*-period that is approximately equal to the natural period. The damped period will be referred to as τ_{PID}, and is equal to τ_o.

Recommendations for response setting are:

Method: Ziegler and Nichols

Open loop:

$$\frac{100}{PB} = \frac{1.2}{\tau_{DT} R_R} \qquad (11a)$$

$$I = 2.0\tau_{DT} \qquad (11b)$$

$$D = 0.5\tau_{DT} \qquad (11c)$$

Closed loop

$$PB = 1.66(PB)^* \qquad (12a)$$

$$I = 0.5\tau_o \qquad (12b)$$

$$D = \tau_o / 8 \qquad (12c)$$

Method: Cohen and Coon

$$\frac{100}{PB} = 1.35\left[\frac{\left(1+\frac{\mu}{5}\right)}{\tau_{DT} R_R}\right] \tag{13a}$$

$$I = 2.5\tau_{DT}\left[\frac{\left(1+\frac{\mu}{5}\right)}{\left(1+\frac{3\mu}{5}\right)}\right] \tag{13b}$$

$$D = \frac{0.37\tau_{DT}}{\left(1+\frac{\mu}{5}\right)} \tag{13c}$$

Method: Shinskey

PB=4.0(PB)* (14a)

$I=0.5\tau_o$ (14b)

$D=0.12\tau_o$ (14c)

Typical responses of a PID controller for several integral and derivative times are shown in Figure 8.

4.0 GENERAL OPERATING PROCEDURE

4.1 General Start-Up Procedure

1. Ensure that all valves are set according to Initial Valve Positions outlined as follows:-

Open	***Close***	***Partially open***
HV 204	HV 201	HV 202
		HV 203

2. Fill in Sump Tank (T-201) with water to 90% full. Close HV 204.

3. Switch on the control panel power supply.

4. Turn on P-201 and manually regulate HV 202 and HV 203 such that 90% of water by-pass back to sump tank.

Warning! *Extra care should be taken to ensure water level doesn't overflow or empty. Failure of doing so may result circulating pump running dry.*

4.2 General Shut-Down Procedure

1. Switch off P-201.
2. Open HV 201 to drain all the water.
3. Switch off the control panel power supply.

5.0 EXPERIMENTAL PROCEDURE

5.1 Close Loop Proportional Level Control

Objective: To demonstrate the characteristics of Proportional control on a Level Control Loop

Procedure :

1. Enter PB value of 100%, I value of 0 seconds, and D value of 0 seconds in LIC-201 control loop.
2. While the control loop is in "**Manual**" mode, adjust the set point to 50%.
3. Tune the output, **MV** gradually so that the level measurement, **PV** matches the set point at 50%.
4. Put the LIC-201 control loop into "**Auto**" mode.
5. Simulate a set point change by increasing the set point to 75%. Observe the response of the controlled and manipulated variables.
6. Put the LIC-201 into "**Manual Mode**", and manually adjust the set point to 50%.
7. Manually adjust the output **MV** gradually so that the level measurement matches the set point of 50%.
8. With the I and D values maintained, repeat step 2 - 7 with the following PB value:

PB
50
10

Note: Compare all the results, and comment on the differences.

5.2 Close Loop Proportional and Integral Level Control

Objective: To demonstrate the characteristics of Proportional and Integral control on a Level Control Loop

Procedure :

1. Enter PB value of 100%, I value of 5 seconds, and D value of 0 seconds in LIC-201 control loop.
2. While the control loop is in "**Manual**" mode, adjust the set point to 50%.
3. Tune the output, **MV** gradually so that the level measurement, **PV** matches the set point at 50%.
4. Put the LIC-201 control loop into "**Auto**" mode.
5. Simulate a set point change by increasing the set point to 75%. Observe the response of the controlled and manipulated variables.
6. Put the LIC-201 into "**Manual Mode**", and manually adjust the set point to 50%.
7. Manually adjust the output **MV** gradually so that the level measurement matches the set point of 50%.
8. With the PB and D values maintained, repeat step 2 - 7 with the following I value:

I
10
30

Note: Compare all the results, and comment on the differences.

5.3 Open Loop Single PID Control Tuning (Ziegler & Nichols Method)

Objective: To demonstrate the characteristics and loop tuning procedures of Single Level Control Loop via Open Loop Ziegler & Nichols Method

Procedure :

1. Put control loop LIC-201 into "**Manual Mode**" and adjust the control loop output "**MV**" to 30%, wait until PV value is stabilized.
2. Make a step change by increasing the LIC-201 output **MV** to 50%, wait until PV value is constant.
3. Open up "**Trend History Window**", measure the dead time, time taken for step change to stabilize, and total change in PV.
4. Referring to the table below, calculate for proportional, integral and derivative values:-

Proportional Gain (PB)	***Integral Time (TI)***	***Derivative Time (TD)***
PB = 83.3 RR T_d	$T_I = 2\ T_d$	$T_D = 0.5\ T_d$

5. Put LIC-201 into "**Manual Mode**", and manually adjust the set point to 50%.
6. Manually adjust the output MV gradually so that the level measurement matches the set point of 50%.
7. Input the calculated PID values into the controller and put the LIC-201 into "**Auto Mode**". Simulate a set point change by increasing the set point to 75%. Observe the response of the controlled and manipulated variables.
8. Adjust (increase) the PB until the desired degree of damping is achieved.
9. Put the LIC-201 into "**Manual Mode**", and manually adjust the set point to 50%.
10. Manually adjust the output MV gradually so that the level measurement matches the set point of 50%. Input the tuned PID values into the controller and put the LIC-201 into "**Auto Mode**".
11. Simulate a load change by fully open HV 202 for 5 seconds and restore it back to its original position. Observe the response of the controlled and manipulated variables.
12. Once the measurement stabilizes, put the LIC-201 back into "**Manual Mode**".
13. Manually adjust the LIC-201 output **MV** gradually so that the level measurement matches the set point of 50%.
14. Put the LIC-201 into "**Auto Mode**".
15. Simulate a set point change by increasing the set point **SV** to 75%. Observe and record the response of the controlled and manipulated variables.

6.0 EQUIPMENT MAINTENANCE

1. Wipe off any spillage on the unit immediately
2. Always check that all indicators are functioning.
3. Clean the equipment with damp cloth every month.

7.0 SAFETY PRECAUTIONS

1. All operating instructions supplied with the unit must be carefully read and understood before attempting to operate the unit.
2. Always check and rectify any water leakage.
3. Do NOT connect power if the appliance is damaged or even partially wet.
4. Only properly trained staff shall be allowed to carry out any servicing or repair job .