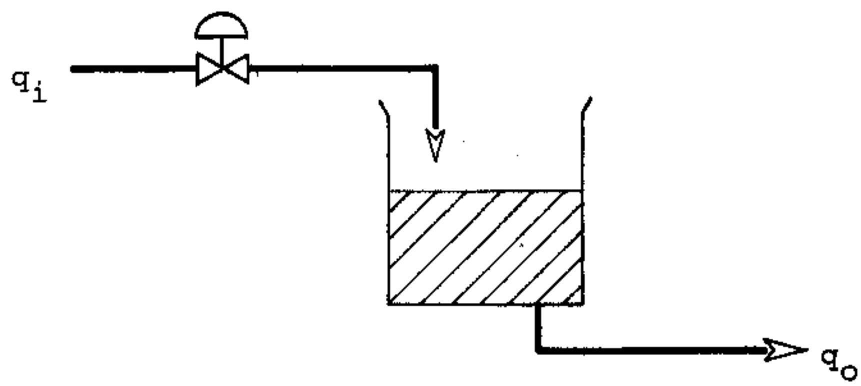
Instrumentation & Control - Course 136

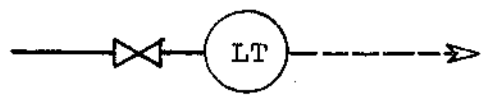
CONTROL THEORY REVIEW

Consider the level control of an open tank with a variable demand outflow and variable inflow regulation by control valve throttling.



Clearly, the level will only remain constant when the inflow (q_i) just equals the outflow (q_o). If the demand increases, the level will begin to drop off until the inflow has increased sufficiently to provide a mass balance and stablize the level.

A transmitter is required for measuring the tank level and developing a signal that can be displayed remotely for level indication, alarm monitoring or be input to a computer or an analog controller for level control. An electronic transmitter produces a 4-20 ma (now accepted as the industry standard) or a 10-50 ma signal representative of process variation. If the transmitter was suitably calibrated the signal will vary linearly from 4-20 ma as the tank level changes from 0-100%. The transmitter is just the control loop data link with the process. The current process state will be continually advised by the transmitter in an analog fashion.

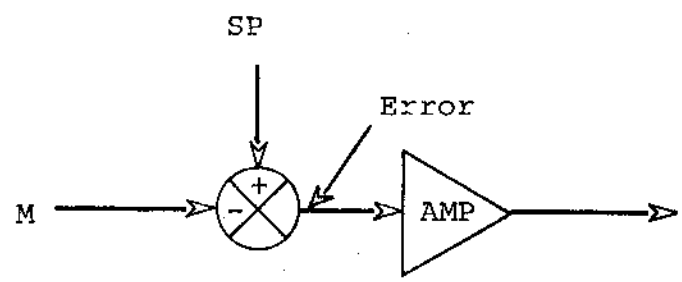


LT: Level Transmitter

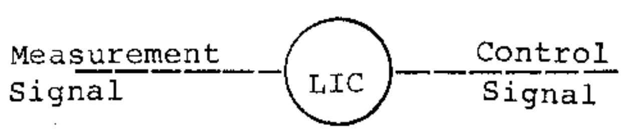
The transmitter signal can be monitored by an electronic controller which is a voltage input device. A dropping resistor is placed in the current loop to develop the required voltage signal. For example a 250 Ω dropping resistor will develop 1-5 VDC from a 4-20 ma signal. The transmitter signal or measurement signal can be compared to the set point (desired operating point) to determine the process error sign and magnitude.

ERROR = SET POINT - MEASUREMENT
E = SP - M

This error can now be suitably amplified by the controller to produce a corrective control signal of 4-20 ma.

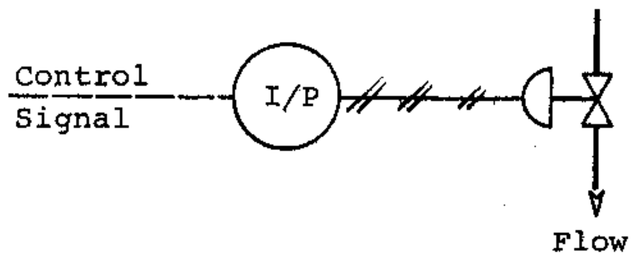


This can be represented in symbol form as follows:

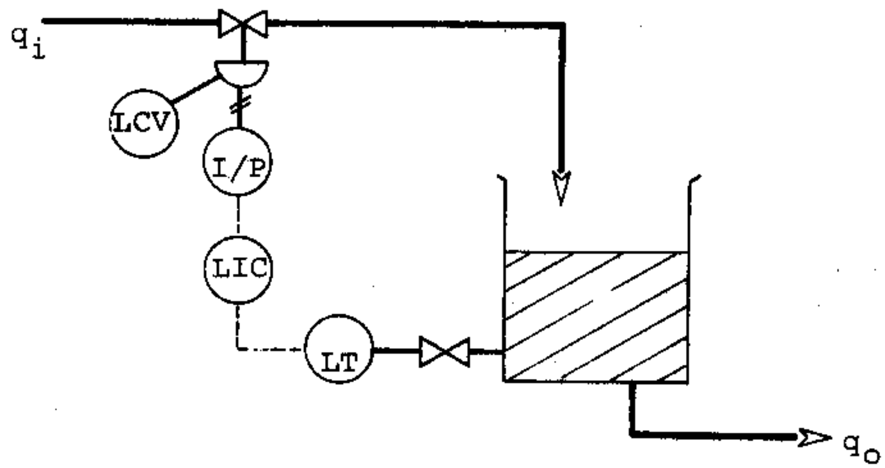


LIC: Level Indicating Controller

The control (output) signal is applied to a field mounted transducer (I/P) which converts the 4-20 ma electronic signal to an equivalent 20-100 kPag pneumatic signal. The pneumatic signal provides the driving force to position the spring opposed diaphragm actuated control valve.



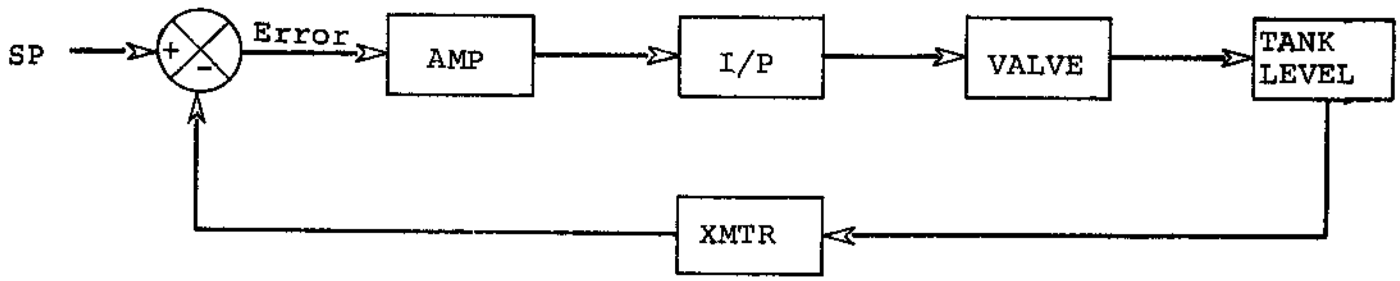
The complete loop with all the equipment combined would result in an operative, closed loop, negative feedback control system.



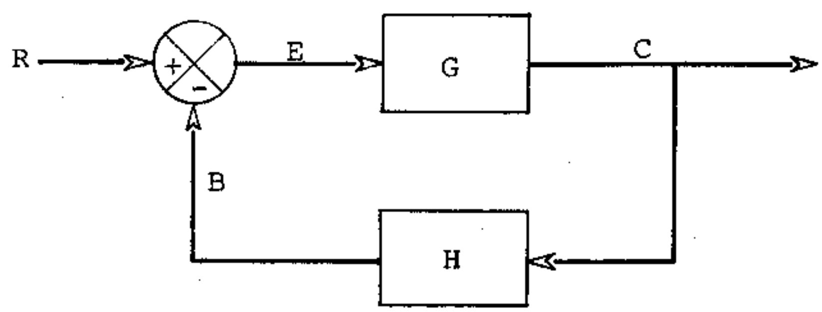
Assume the control valve is an air to open style; increasing the pneumatic signal to the valve will drive it more open. The controller must now respond to process deviations in a particular fashion defined as the **controller action.** A controller with direct action will respond to a process deviation above the set point by increasing the control signal. That is to say, an **increasing** measurement results in an **increasing** control signal. Direct action is shown as (increasing, increasing) or (↑↑). Following this same reasoning, reverse action will be shown as (increasing, decreasing) or (↑↓).

The controller action required for the level control system developed must be reverse. As the level rises above the set point, the control signal will decrease, allowing the valve to go more closed. Control actions are changed in electronic controllers by simply positioning a switch so that a controller is easily adapted to the requirements of the system.

The level control loop can also be sketched in block form rather than as a physical system.



For general representation, this sketch can be simplified by considering the control amplifier, I/P, valve, and process blocks to be combined into one block designated as the forward gain block G.



R = Reference input or set point
E = Error, deviation from set point
G = Forward loop gain operator for controller, valve, etc
H = Feedback gain operator representing the transmitter
B = Feedback signal
C = Controlled variable (level in this example)

Ideally, the controlled variable should be maintained at the set point by the control system. The ratio of controlled variable to set point (C/R) can be calculated by referring to the previous closed loop sketch. From the sketch:

$$E = R - B, \ EG = C, \ CH = B$$

$$E = R-B$$

$$\frac{C}{G} = R - CH$$

$$C = GR - CHG$$

$$C + CHG = GR$$

$$C(1 + HG) = GR$$

$$\frac{C}{R} = \frac{G}{1 + HG}$$

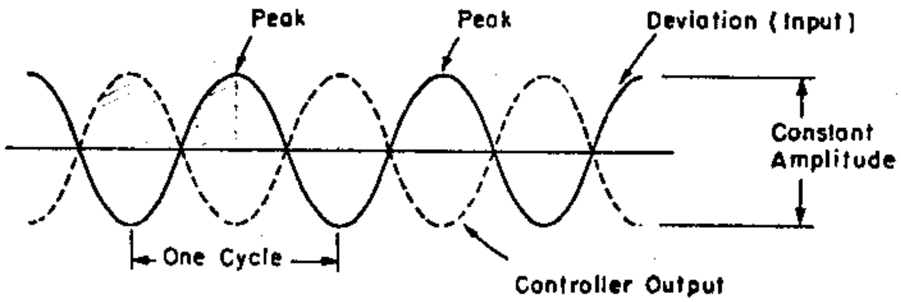
This ratio of $\frac{C}{R}$ is called the control ratio. Later in the course this ratio will be referred to as the closed loop transfer function and will describe the ratio of controlled variable to input excitation as a function of the disturbance frequency. The control ratio in the frequency domain would appear as:

$$\frac{C(jw)}{R(jw)} = \frac{G(jw)}{1 + H(jw)\ G(jw)}$$

Consider the system developed so far being subjected to a disturbance such as a step increase in demand with the level controller only able to provide on/off control (like a house thermostat). The valve will be driven fully open or closed depending on the process position wrt the set point. As soon as the process reaches the set point, the valve will drive to the other extreme. It should be relatively easy to visualize the resulting level control with on/off control. The process will settle out in a continuous cycle about the set point.

Notice that if the level is too high, the inflow valve is driven more closed and vice versa.

The control system must act in **opposition** to the deviation in an attempt to restore the process to the set point. The following sketch represents the process cycling about the set point and the corresponding control system response.



Although the control system reponds to the error, it would be convenient to consider the subsequent process response to the corrective action. Consider the dotted sine waveform representing valve opening and the solid sine waveform representing level variation about the set point.

In the inflow valve is driven open to provide maximum input to the tank, the level should rise. Notice that the level does not peak until 1/2 cycle later. (See the two shaped peaks.) The level response is delayed or is said to lag behind the valve motion by 1/2 cycle or 180°. The difference in phase angle between a sinusoidal output and input is called the phase lag. Consider the instant when the valve opening is peaking negatively and the process curve is peaking positively. The sine angle corresponding to a negative peak will be 270° (sin(270) = -1) while that corresponding to a positive peak will be 90° (sin(90) = 1).

Phase lag = output - input

$$\phi = 90° - 270°$$

$$\phi = -180°$$

The system phase lag will always be negative so that the negative sign is usually deleted, lag being implied.

The system gain can also be considered for this cycling condition. Gain in control theory will be the ratio of percent change in output to percent change in input for some block or device.

$$\text{GAIN} = \frac{\%\Delta \text{ output}}{\%\Delta \text{ input}}$$

Since the amplitude of the cycling is constant, the **loop gain** must be one. Otherwise the amplitude would be attenuated (Gain <1) or the process would drive to some limiting value (Gain 1). Loop gain is simply the combined effect of all gain components in the system, such as controller gain (k_c), valve gain (k_v) and process gain (k_p).

$$\text{Loop gain} = k_c k_v k_p$$

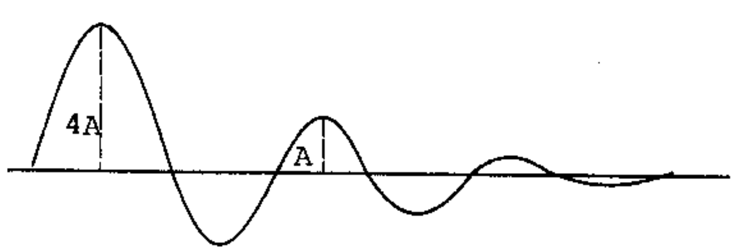
The critical conditions for continuous process oscillations are a loop gain of one and a phase lag of 180°. Such sustained, constant amplitude cycling is defined as **marginal stability.** An operational system should avoid the marginal stability state by ensuring that the loop gain is less than one when the phase lag approaches 180°. The phase lag in a stable system will usually be less than 140° preventing sustained oscillations.

In order to produce a full cycle of oscillation, a total rotational angle of 360° must be present. The controller always introduces a phase angle of 180° by acting in opposition to the process deviation. This constant 180° lag by the controller is ignored in phase considerations. The remaining 180° (to provide 360°) lag is supplied by such things as valve reponse, process capacitance, and dead time.

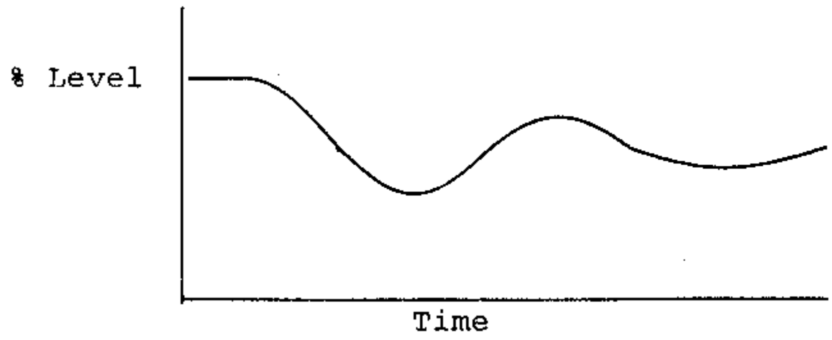
The limitation of on/off control is that the valve will be stroked to its extreme position with an error of 1% or 10%. Even though only a small correction is required, full valve travel (over correction) will result. If the control system could respond **proportional** to the error, a more stable system should result. A variable gain controller is required so that if the process is close to the set point, the valve will be throttled slightly.

Proportional Control

The optimum response of a proportional control system would approximate the quarter decay recovery curve. The quarter decay curve is just underdamped response to a disturbance where each successive positive peak is 1/4 of the previous one.



Consider the level control system under proportional control being subjected to a demand increase. The level fluctuations will be much more stable than was the case under the on/off control.



Level Response Following An Upset

A proportional controller can have setting units of either gain or **proportional band.** Proportional Band (%PB) is defined as the percentage change by the controlled variable about the set point (symmetrical) which will produce a 100% change in control signal.

$$\%PB = \frac{\%\Delta input}{\%\Delta output} \times 100$$

Gain and proportional band are reciprocally related.

$$Gain = \frac{100}{\%PB}$$

Assume that the level varies 10% above and below the set point before the control signal drives through 100% change. The controller must have a proportional band of 20% or a gain of 5.

The output signal of a proportional controller will respond proportional to the error. The manipulated variable is dependent upon the control signal, so allow that the manipulated variable will be varied proportional to the error.

$$m \propto e$$

Including a proportionality constant results in:

$$m = ke$$

m = manipulated variable magnitude,
k = controller gain,
e = process error, deviation from the set point.

In this example the manipulated variable will be adjusted in proportion to the error in an attempt to maintain stable control of the process. If the controller was successful in holding the measurement at the set point, then the error would be reduced to zero. Obviously the manipulated variable cannot be allowed to drop to zero in a dynamic system, so the basic control equation must be modified slightly. A bias term can be included to provide a control signal value if the error is zero.

$$m = ke + b$$

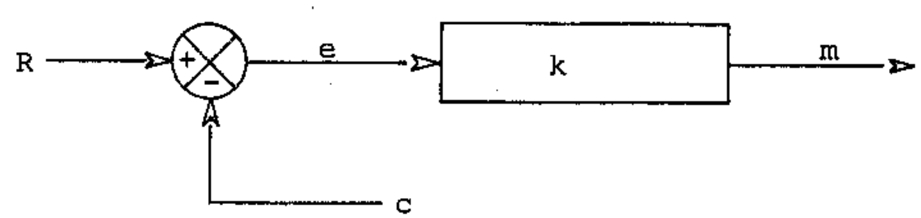
b = bias term

The bias term is supplied so that the control signal will drop to zero when the process is at the set point. In general the bias value is considered to be 50% of the control signal for an ideally aligned proportional controller. That is the control signal output of a perfectly aligned proportional controller will be 50% when the measurement equals the set point regardless of the controller gain.

The formula representing proportional control is achieved by substituting $\frac{100}{\%PB}$ in place of k.

$$m = \frac{100}{\%PB} e + b$$

The block diagram commonly used to represent a proportional controller is shown below:



R = reference input or set point,
k = controller gain,
m = manipulated variable,
c = feedback signal from the controlled variable,
e = error.

The proportional band of the controller would be adjusted to provide optimum control of a given process. If a transient disturbance occurs the controller will stroke the valve in proportion to the error to provide corrective action.

Offset

Proportional only control will result in a process **offset** if the process supply or demand conditions of the system have been varied. Offset is defined as the stable deviation of a process away from the set point after a proportional only control system has responded to a process supply or demand change. Imagine a system under proportional control in which the error has been reduced to zero with m = b = 50%. If the %PB = 50, and a load change requires the manipulated variable to rise to 60% to achieve equilibrium; then determine the error required to provide this value of m.

$$m = \frac{100}{\%PB} e + b$$

$$60 = \frac{100}{50} e + 50$$

$$10 = 2e$$

$$e = 5\%$$

If the proportional band was 200%, calculate the offset which would result.

$$m = \frac{100}{\%PB} e + b$$

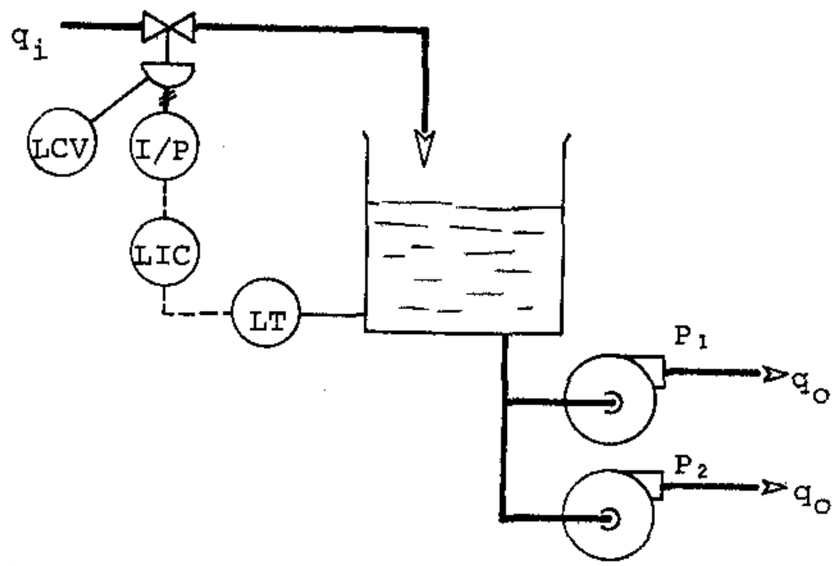
$$60 = \frac{100}{200} e + 50$$

$$10 = .5e$$

$$e = 20\%$$

The offset is a function of the proportional band and can be a substantial error depending upon the proportional band and the magnitude of the load disturbance. Clearly this type of steady state error would not be acceptable in many control systems. Note that the problem of offset can not be corrected by narrowing the proportional band since the system might then be driven to instability by excessive loop gain.

A practical example of offset can be shown using a level system with a variable demand represented by two pumps.



System Data

Controller Scale = 0 - 100%
Set point = 60%
% PB = 50%
Valve = 0 - 200 l/min, linear flow characteristics
P_1 = 100 l/min
P_2 = 40 l/min

Initially, only P_1 is running, the level is at the set point and stable. Since the measurement is at the set point, the control signal will be 50% (bias value). Inflow will be 50% of 200 l/min or 100 l/min which just matches the outflow due to pump P_1.

Pump P_2 is now switched on simulating a demand increase, outflow exceeds inflow and the level begins to drop. The level controller responds proportional to the error and drives the valve more open until the inflow matches the outflow. The level must drop enough so that the error modified by the controller gain will stroke the valve sufficiently to restore equilibrium.

Calculation of Offset

Initial outflow: 100 + 40 = 140 l/min
Initial inflow : 100 l/min
Required change in inflow: +40 l/min

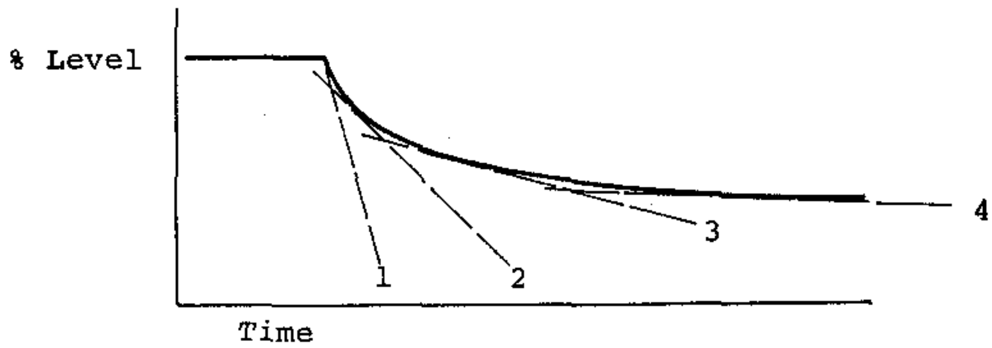
$$\text{Required } \%\Delta\text{valve: } \frac{40}{200} \times 100 = 20\%$$

$\%\Delta$output = Gain x % error
20 = 2 x % error
%error = 10 (this is the offset)

The level must drop 10% before the inflow again matches the outflow and the level stops dropping. An offset of 10% would exist in this particular case.

Straight line approximations can be used to sketch such a control response. Initially the level will drop at a maximum rate (line 1) since there is the greatest mismatch between inflow and outflow. As the level drops, the controller will drive the control valve more open to decrease the mismatch so that the level will not drop so rapidly (line 2).

The rate of level drop will decrease until the level is eventually held steady at the new offset position (line 4).



A second control mode, **reset** or **integral** mode is required to eliminate offset.

Reset Mode

Reset or integral mode is selected to eliminate offset in a control system. The offset problem in the previous example can be corrected by opening the inflow valve more than the equilibrium proportional response requires. Reset mode will integrate the error, changing the control signal until the measurement is brought back to the set point.

Consider the proportional response to a given process change. If the error is not zero, reset mode will begin to contribute to the control signal. The time required for reset to duplicate the original proportional response can be noted in minutes. This time is called the **reset time** and is the number of minutes required to repeat the original proportional response. Reset time is stated in Minutes Per Repeat (of the proportional response) and is designated as MPR.

Some manufacturers mark the integral mode setting in reset rate units of Repeats (of proportional response) Per Minute (RPM). Reset time and reset rate are reciprocally related.

$$MPR = \frac{1}{RPM}$$

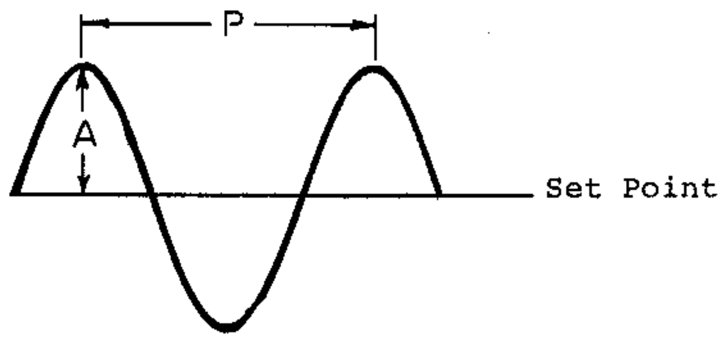
eg, 5 MPR is equivalent to 0.2 RPM.

Pure integral mode output can be represented as:

$$m = \frac{1}{R} \int_o^t edt$$

m = manipulated variable
e = error
R = reset time in MPR

Assume that the process to be controlled has a sinusoidal error developed about the set point.



This error can described by the general function:

$$e = A \sin\left(\frac{2\pi t}{P}\right)$$

e = error
A = amplitude
t = time
P = period

The integral mode output will be:

$$m = \frac{1}{R} \int_o^t A \sin\left(\frac{2\pi t}{P}\right) dt$$

$$m = -\frac{AP}{2\pi R} \operatorname{Cos}\left(\frac{2\pi t}{P}\right) \Big|_o^t$$

$$m = -\frac{AP}{2\pi R} \operatorname{Cos}\left(\frac{2\pi t}{P}\right) + \frac{AP}{2\pi R}$$

Allow that $m_o = \frac{AP}{2\pi R}$, the manipulated variable value at time zero.

$$m = -\frac{AP}{2\pi R}\,\text{Cos}\,\left(\frac{2\pi t}{P}\right) = m_o$$

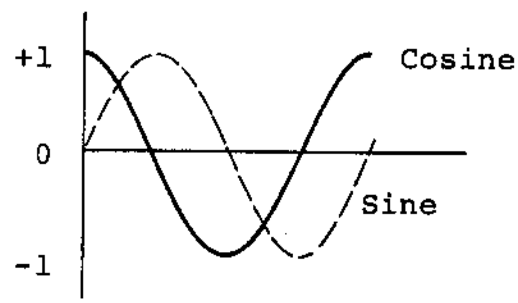
The effect of reset mode on the loop gain and phase angle should be determined. The gain of the integrator can be found from the ratio of the integrator output amplitude to input amplitude.

$$G_R = \frac{AP/2\pi R}{A} = \frac{P}{2\pi R}$$

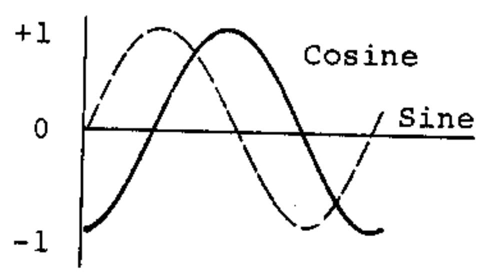
For any given cycle period, the gain of the integrator depends upon the reset time selected. Notice that reset mode gain will decrease as the period of cycling decreases. Reset can be considered as supplying high steady state gain for the elimination of offset, but will have a limited gain contribution for a transient disturbance.

In order to find the phase angle contribution of rest mode, the output and input angles must be compared. The input to the integrator unit was the function Sin $\left(\frac{2\pi t}{P}\right)$ while the output is -Cos $\left(\frac{2\pi t}{P}\right)$.

Graphically a cosine function leads a sine function by 90°.



A negative cosine function will be inverted so that the output will lag the input by 90°.



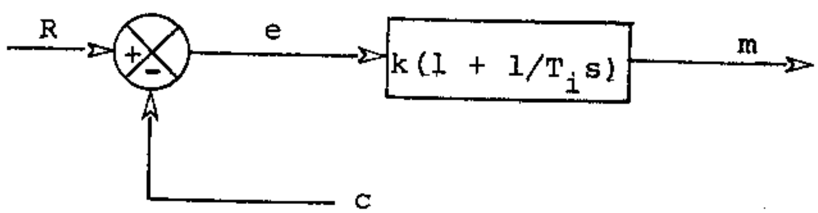
An ideal integrator exhibits a 90° phase lag regardless of the period of the input. Since phase lag is an undesirable quality, the addition of reset to a control system is a trade off between the elimination of offset and decreasing the stability of the system.

Proportional Plus Reset

This control combination allows the response speed and stability of proportional control while eliminating offset from the system. The general formula representing this two mode combination is:

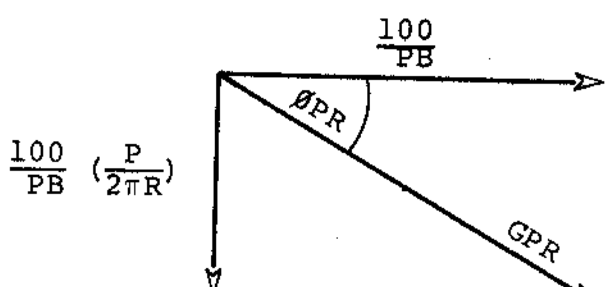
$$m = \frac{100\%}{\%PB}\left(e + \frac{1}{R}\int_0^t e\,dt\right)$$

The following block diagram is commonly used to represent proportional plus reset control.



T_i = integral time or reset time (MPR)

Since both gain and phase considerations are involved, the combination of proportional plus reset control can be represented by vector methods.



$$(G_{PR})^2 = \left(\frac{100}{PB}\right)^2 + \left(\left(\frac{100}{PB}\right)\left(\frac{P}{2\pi R}\right)\right)^2$$

$$G_{PR} = \frac{100}{PB} + \left(1 + \left(\frac{P}{2\pi R}\right)^2\right)^{1/2}$$

$$\mathrm{Tan}(\phi) = \frac{\frac{100}{PB}\left(\frac{P}{2\pi R}\right)}{\frac{100}{PB}} = \frac{P}{2\pi R}$$

$$\phi_{PR} = \tan^{-1}\left(\frac{P}{2\pi R}\right) \quad \text{(lag)}$$

It has been found that optimum control will be obtained with a proportional plus reset controller if reset contributes appoximately 11° lag at the marginal stability condition. Reset would be specified on a system where offset can not be tolerated and the system could be subjected to process supply or demand changes. Examples of proportional plus reset control would be steam drum level control, or feedwater flow control.

If reset time is too low for the process application, then reset mode will change the signal faster than the process can respond. The signal will be integrated past the normal limits (above 20 ma in a 4-20 ma loop) by reset. The valve can only be physically fully opened or completely closed even though the signal exceeds its normal range limits. When the process finally does respond to the valve being at the extreme position, the process must cross the set point (change the sign of the error) before the reset term begins to integrate back down. The net effect is a cycling process more extreme than on/off control since the valve does not begin to change status until after the set point is crossed. This condition where the control signal exceeds normal limits due to reset action is referred to as **reset wind-up.**

The following simplified control program demonstrates the potential problem of reset wind-up.

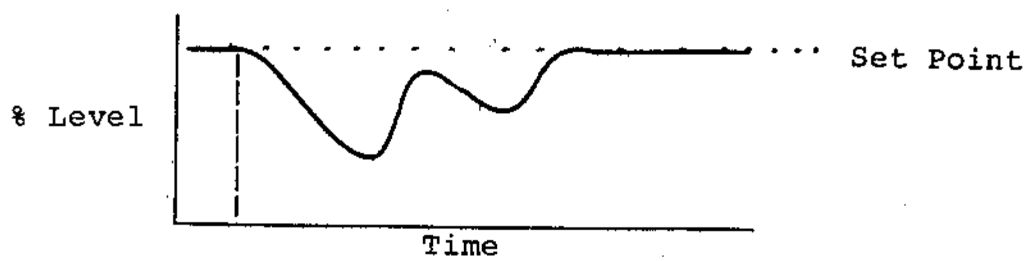
PROGRAM

```
Sum = 0 ............................initialize summing location
100 Read T .........................determine temperature
E1 = Set-T .........................calculate error
Sum=Sum + E1 .......................increment sum
SIG = k*(E1 + Sum/R)................calculate signal

Output SIG .........................apply signal to DAC
   service other loops
Go to 100
```

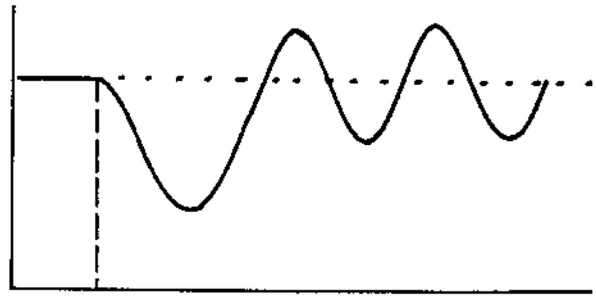
Assume that the proportional plus reset temperature control loop is executed once each second and the error (E1), sum value (Sum) and % signal (SIG) are recalculated each second. If a particular error, say 5%, exists and the process is slow to respond, then every second the sum will be incremented by 5%. Imagine the consequences of this constant 5% error being summed every second for three minutes if the reset time is very low. The reset term becomes very large wrt the proportional term so that even though the process is eventually restored to the set point, the signal does not change significantly. The process must now rise above the set point so that the sign of the error will change and then the reset mode can begin to integrate the excessive signal back down (effectively Sum = Sum - E1).

A properly adjusted proportional plus reset controller should restore the process to the set point in a stable fashion following a process supply or demand change.



Correct Reset Time

If excessive reset rate is applied, then the resulting over correction will result in the process cycling about the set point. Reset cycling is caused by too many RPM or too low a setting MPR.



Reset Rate Too Fast

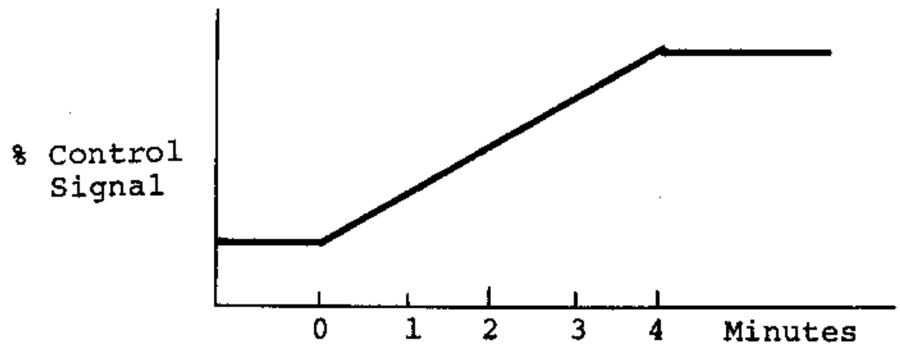
Derivative Mode

Derivative mode or **rate** mode responds to the rate of change of the deviation of the process from the set point. Derivative mode can be achieved by taking the first derivative of the error.

$$m = D \frac{de}{dt}$$

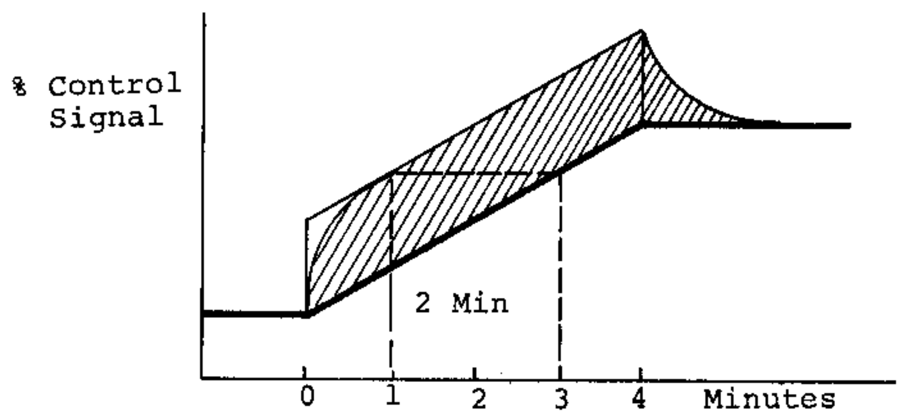
m = manipulated variable
D = derivative time in minutes
e = error

Derivative time is the time advance of the control signal with proportional plus derivative control over the response to the same disturbance with only proportional control. Derivative response is easily visualized for a system which is subjected to an error which changes linearly wrt time. (Say 2%/min.) The **proportional** response will be a ramp keyed by the changing measurement and dependent upon the controller gain.



Proportional Response to a Ramp Disturbance

Derivative mode will only respond while the error is changing. Assume a derivative time of 2 minutes, then derivative will cause the control signal to be now, that signal value that proportional would cause two minutes from now; while the error is changing at the same rate.



Proportional Plus Derivative Response

Practical derivative response will be somewhat rounded as the error just begins to change or just stops changing. (Similar to charging or discharging in an RC circuit.) The net effect of the larger magnitude control response will be a smaller process deviation away from the set point and improved stability since derivative is acting to oppose a changing error. (Braking effect.)

Consider the response of a pure derivative device being subjected to a sinusoidal error.

$$m = D\frac{de}{dt} = D\,\frac{d(A\sin(\frac{2\pi t}{P}))}{dt}$$

$$m = \frac{DA2\pi}{P}\,\cos(\frac{2\pi t}{P})$$

The input function is $\sin(2\pi t/P)$ while the output function is $\cos(\frac{2\pi t}{P})$. The output must lead the input by 90° due to the relationship of sine and cosine functions. An ideal derivative mode exhibits a phase lead of 90° regardless of the period of the input.

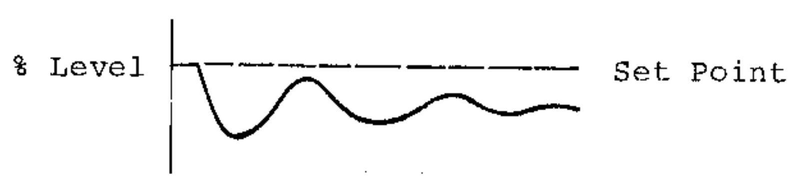
Gain for the pure rate mode is found from the ratio of output amplitude to the input amplitude.

$$G_D = \frac{\frac{DA2\pi}{P}}{A} = \frac{2\pi D}{P}$$

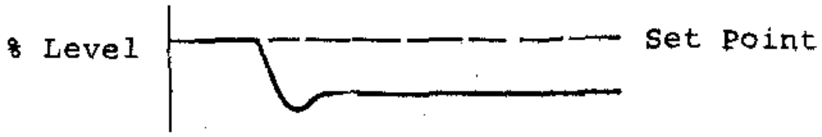
Notice that if the natural period is short, then the gain of the derivative mode will be large. There will be large derivative gain from a high frequency disturbance.

Noise in a high frequency process will be amplified considerably by an ideal derivative unit. This is why derivative mode is not specified for fast processes such as flow. The resulting over correction and prompt process response will soon result in uncontrolled cycling. A high limit is always placed on derivative gain to prevent high frequency instability. This derivative gain limit is usually about ten and is called the rate amplitude. The magnitude of the rate amplitude is set during the instrument manufacture.

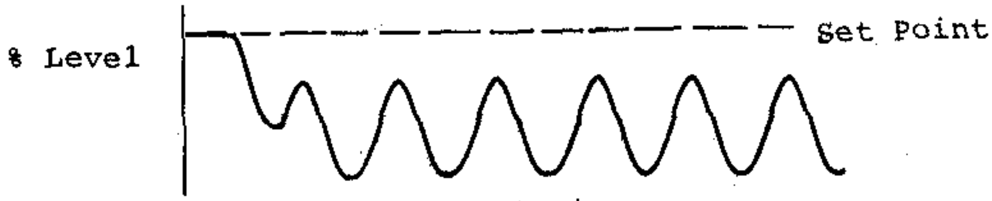
There is one best setting for derivative time for any given process. Too much derivative time will stroke the valve excessively resulting in process cycling with a short period.



%PB Response to a Step Change



%PB + Correct Rate Response



Too Much Rate Action

The correct adjustment of derivative mode should minimize the process deviation and maximize the stability of the application.

Proportional Plus Derivative Control

This two mode automatic control combination can be represented in general by:

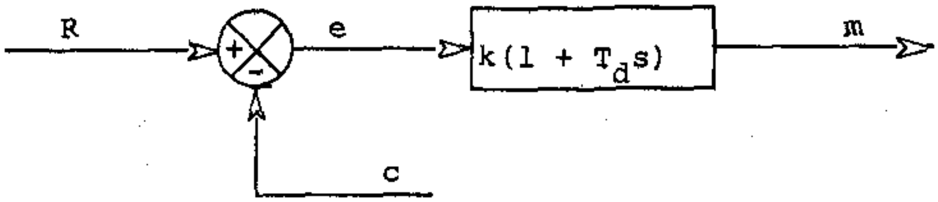
$$m = \frac{100}{\%PB} \left(e + D \frac{de}{dt}\right) + b$$

Notice that the bias term is required for this combination since control will revert to straight proportional in the steady state. If the error stops changing then $\frac{de}{dt} = 0$ and the control equation becomes:

$$M = \frac{100}{\%PB} (e) + b$$

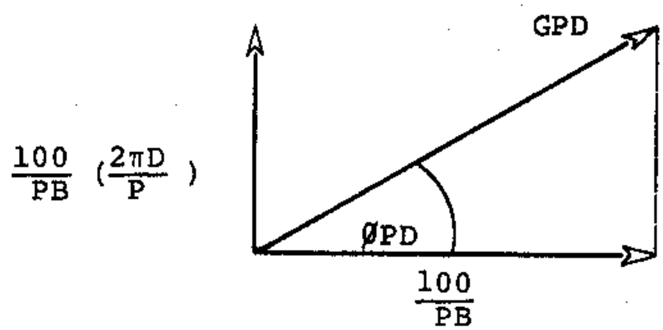
A control system with proportional plus derivative control will still experience offset when subjected to a process supply or demand change. Reset must be included if offset is a problem in the control system.

The following block diagram represents a proportional plus derivative controller.



T_d = Derivative time in minutes.

The resulting gain and phase angle for a proportional plus derivative controller can be determined by the same vector methods used with the proportional plus reset model.



$$(G_{PD})^2 = \left(\frac{100}{PB}\right)^2 + \left(\left(\frac{100}{PB}\right)\left(\frac{2\pi D}{P}\right)\right)^2$$

$$G_{PD} = \frac{100}{PB} \left(1 = \left(\frac{2\pi D}{P}\right)^2\right)^{1/2}$$

$$\mathrm{Tan}(\phi) = \frac{\frac{100}{PB}\left(\frac{2\pi D}{P}\right)}{\frac{100}{PB}} = \frac{2\pi D}{P}$$

$$\phi_{PD} = \tan^{-1}\left(\frac{2\pi D}{P}\right) \quad \text{(lead)}$$

Empirical results from operative loops have shown that a maximum lead of 40° would be the practical phase contribution limit for a proportional plus derivative controller. The derivative mode would be adjusted to produce this lead at the marginal stability condition. This lead contribution effectively shifts the frequency at which the 180° lag occurs to a higher value improving the stability of the system.

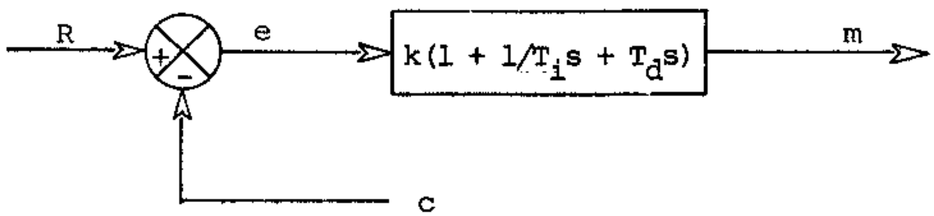
Theoretical Three Mode Controllers

The three modes discussed can be combined to form a proportional plus reset plus derivative controller (PID). This will result in a controller which can respond proportional to the deviation and the rate of deviation while eliminating the steady state error. This combined function can be represented mathematically as:

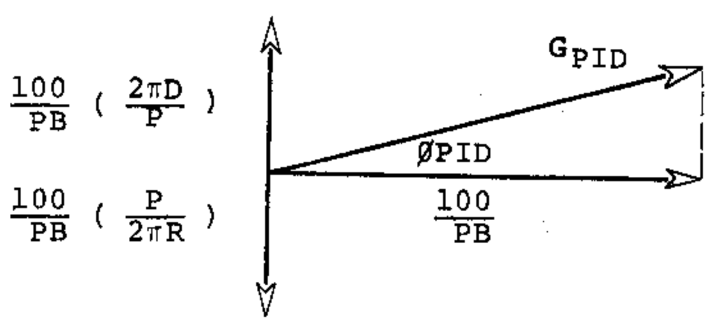
$$m = \frac{100}{PB}\left(e + \frac{1}{R}\int_{o}^{t} e\,dt + D\frac{de}{dt}\right)$$

Notice that with the addition of reset, the bias term is not required since the integration of the error provides a floating bias value.

The block diagram representing a three term controller is shown in the following sketch.



The resultant gain and phase angle is dependent on the mode settings selected and the frequency of the process disturbance. The derivative time will always be set to provide a larger lead contribution than the lag from reset, so that a net phase lead will result to aid stabilization. The resultant three mode vector representation will be:



$$(G_{PID}) = \left(\frac{100}{PB}\right)^2 + \left(\left(\frac{100}{PB}\right)\left(\frac{2\pi D}{P} - \frac{P}{2\ R}\right)^2\right)^2$$

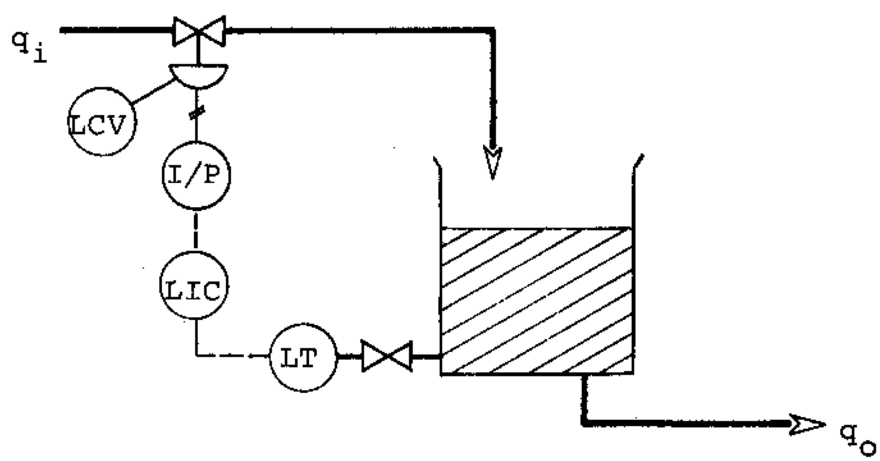
$$G_{PID} = \frac{100}{PB}\left(1 + \left(\frac{2\pi D}{P} - \frac{P}{2\pi R}\right)^2\right)^{1/2}$$

$$\mathrm{Tan}(\phi) = \frac{\frac{100}{PB}\left(\frac{2\pi D}{P} - \frac{P}{2\pi R}\right)}{\frac{100}{PB}} = \frac{2\pi D}{P} - \frac{P}{2\pi R}$$

$$\phi_{PID} = \tan^{-1}\left(\frac{2\pi D}{P} - \frac{P}{2\pi R}\right) \quad \text{(lead)}$$

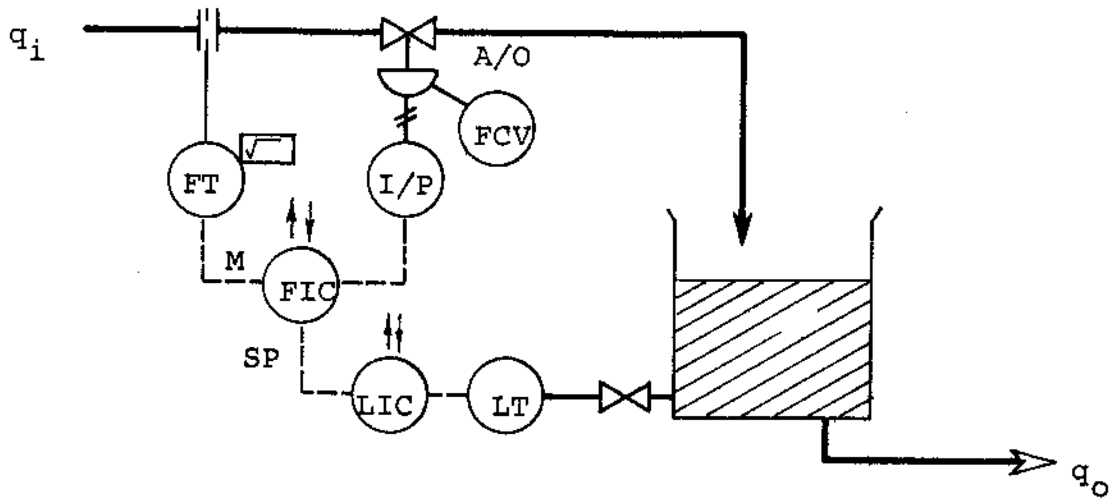
Since the lag of reset is offset by the lead of rate, a greater amount of reset rate can be used in a three term controller than is possible with only proportional plus reset. A net lead of 25° is the expected phase contribution from an optimumly tuned three mode controller.

Cascade Control



Consider this level system being subjected to a demand disturbance followed by a supply disturbance. If a demand increase occurs the tank level will begin to drop. The level controller will respond proportionally, stroking the valve to a new position in an attempt to stop the level from dropping further. Should a supply decrease occur at this time, the flow through the valve will be less than expected for the given valve position. Tank level will now drop further from the set point until equilibirium can again be restored. Minimizing this sort of upset would be desirable in many applications.

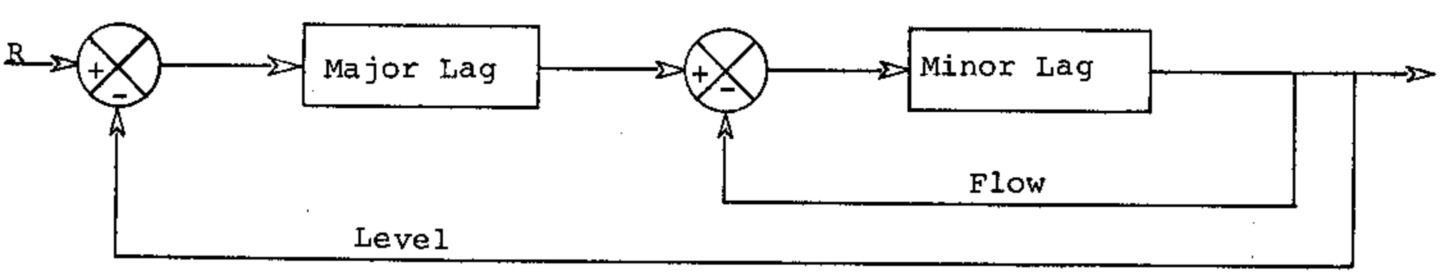
The problem can be simplified by realizing that the supply disturbance is the only addition to this system compared to previous examples. If the flow fluctuations can be steadied, then the level system should perform adequately. A flow control loop can be placed on the inflow line and a command for a particular flow can be developed by the level controller.



This control combination is called a cascade system. The control signal output from the level controller is now the set point for the flow controller. Both controllers in this system must be reverse action. The flow controller action is dictated by the valve in the flow system. The level controller is reverse action since an increase in level requires a decrease in flow.

If a demand increase occurs, the tank level begins to drop and the output of the level controller will increase. This signal will raise the set point of the flow controller, effectively calling for increased inflow. Should a supply decrease occur, the drop in flow is sensed by the flow transmitter and compared to the requested set point of the flow controller. The flow valve is throttled as necessary to hold the flow at the requested rate. Flow disturbances are eliminated before they can disturb the large capacitance, slower responding level system.

The general format for a cascade system is for the major lag controller to develop the set point for the minor lag controller. (Major lag sets Minor lag.)



The major lag controller is usually referred to as the **primary** controller. The output of the primary controller is then the set point for the minor lag or **secondary** controller. After finishing 136.00-3 (Control Mode Settings), consider how you would start up and tune a cascade system such as this level control example.

ASSIGNMENT

1. Sketch an electronic control loop used to maintain the temperature of D_2O leaving a heat exchanger. The effluent temperature is sensed by a surface mounted RTD. The valve used on the cooling service water line must fail open in the event of lost instrument air. Discuss one cycle of operation and determine the controller action.

2. Sketch a simplified block diagram representing the cascade control of the system in Question 1. Identify the major and minor lags.

3. Sketch the control loop equipment necessary to provide the cascade control of the HX system so that both service water supply variations and bleed flow changes can be corrected. State controller actions.

4. Explain clearly how offset can occur in a proportional controlled system which is subjected to a process supply or demand change.

5. Discuss the net result of using derivative mode on a flow application which can experience a surge flow transient.

6. From a general stability consideration, what is the advantage of derivative and disadvantage of reset mode in a given control system?

7. What is the effect of reset wind-up on a control system?

8. What phase lead will a controller produce if the derivative time is zero minutes? Show this as a vector sketch.

9. A proportional plus derivative controller is utilized on an application where the process cycles 6 times in 2 hours. (Marginal stability.) Control settings of 75% PB and 2 minutes derivative are selected.

   (a) Determine the theoretical resultant gain of this controller.

   (b) Determine the phase angle contribution for this control combination. (lead or lag)

   (c) State if you feel this derivative time is correct based on the empirical model or if the derivative time should be increased or decreased.

   (d) Can you predict what the approximate derivative time should be in minutes? What general information is required? (See 136.00-3, to check your answer.)

10. Assume the application in question 9 is to be controlled with a proportional plus reset controller. Control settings of 75% PB and 4 minutes per repeat for reset are selected.

   (a) Determine the theoretical resultant gain of this controller.

   (b) Determine the phase angle contribution for this combination (lead or lag).

   (c) State if you feel this reset time is correct based on the empirical model or if the MPR should be increased or decreased.

   (d) Can you predict what the approximate reset time should be in MPR? What general information is required? How would you obtain this data?

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D.E. Tennant