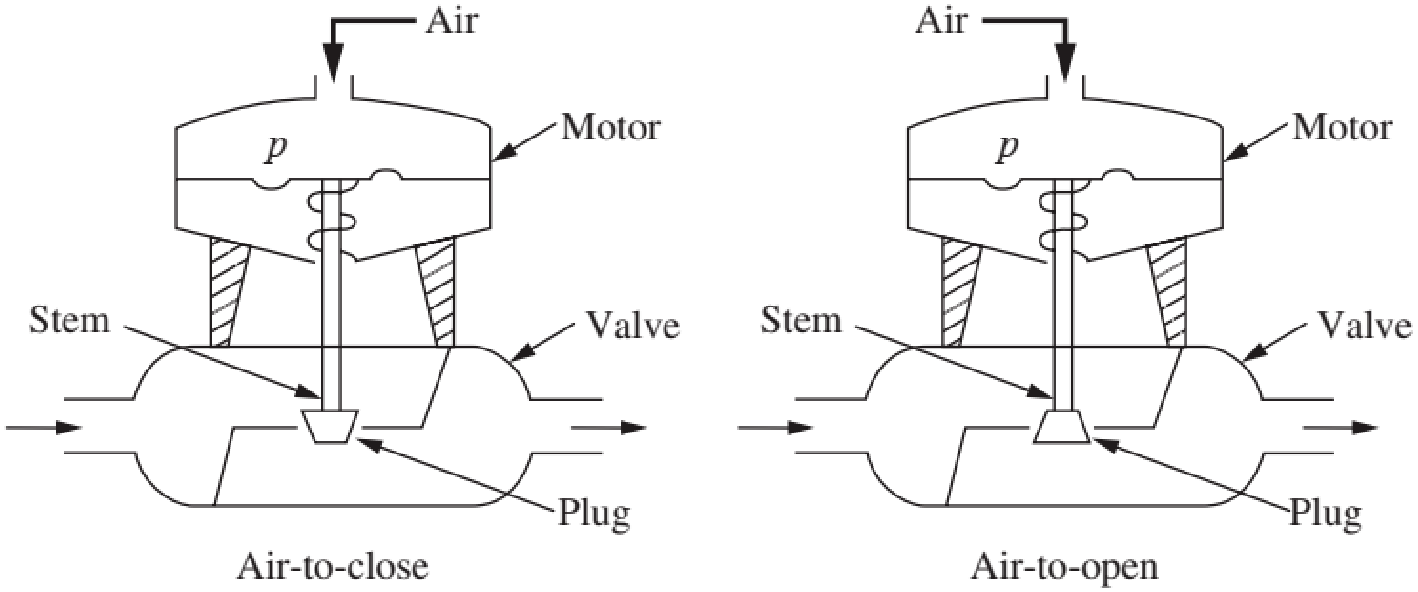
CONTROLLERS
AND
FINAL CONTROL ELEMENTS

CHAPTER 9

- Although pneumatic controllers are still in use and function quite well in many installations.
- Controllers being installed today are electronic or computer-based instruments.
- For this reason, the proportional controller to be discussed in this chapter will be electronic or computer-based.
- Other pneumatic devices, such as control valves, are found throughout chemical processing plants and are a very important part of chemical process control systems.
- The control valve contains a pneumatic device (valve motor) that moves the valve stem as the pressure on a spring-loaded diaphragm changes.
- The stem positions a plug in the orifice of the valve body.
- In the air-to-close valve, as the air pressure increases, the plug moves downward and restricts the flow of fluid through the valve.
- In the air-to-open valve, the valve opens and allows greater flow as the valve-top air pressure increases.

MECHANISMS



- The choice between air-to-open and air-to-close is usually made based on safety considerations.
- If the instrument air pressure fails, we would like the valve to fail in a safe position for the process.
- For example, if the control valve were on the cooling water inlet to a cooling jacket for an exothermic chemical reactor, we would want the valve to fail open so that we do not lose cooling water flow to the reactor. In such a situation, we would choose an air-to-OPEN valve.

- Valve motors are often constructed so that the valve stem position is proportional to the valve-top pressure.
- Most commercial valves move from fully open to fully closed as the valve-top pressure changes from 3 to 15 psig.
- The plug and seat (or orifice) can be shaped so that various relationships between stem position and size of opening (hence, flow rate) are obtained.
- we assume for simplicity that at *steady state* the flow (for fixed upstream and downstream fluid pressures) is proportional to the valve-top pneumatic pressure.
- A valve having this relation is called a *linear valve.*

Controller

- Hardware consists of the following components listed here along with their respective conversions:

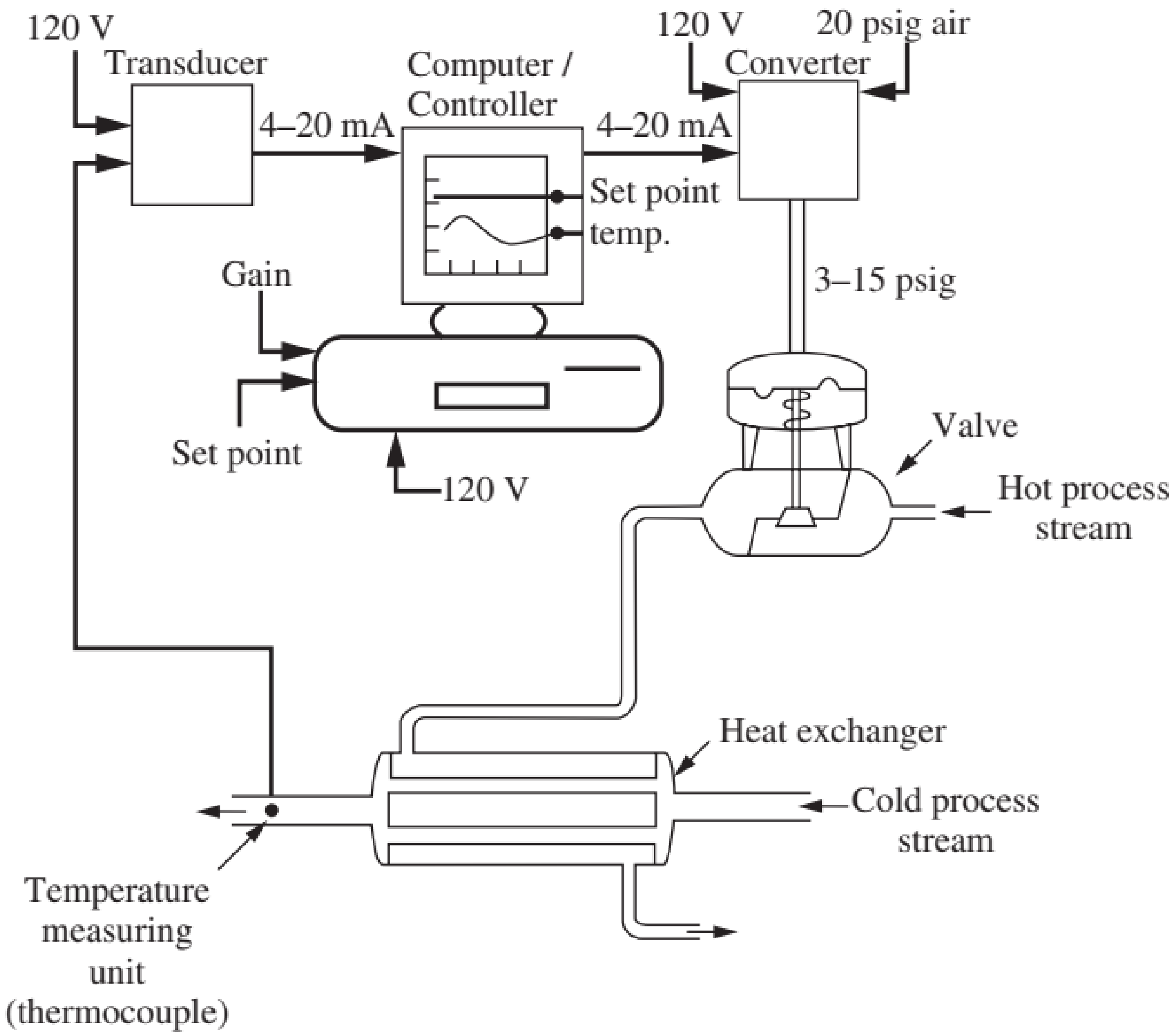
  Transducer (temperature-to-current)

  Computer/ Controller (current-to-current)

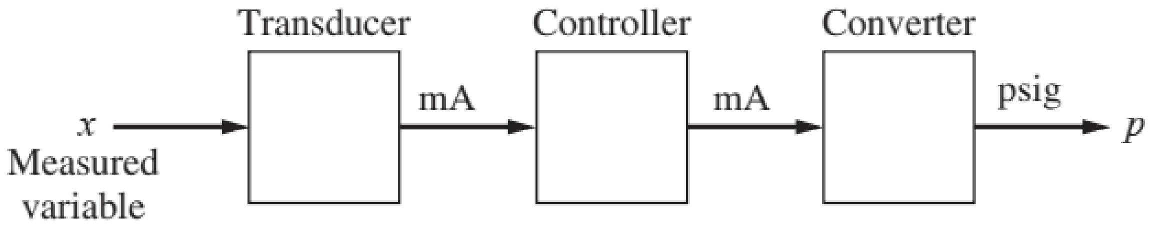
  Converter (current-to-pressure)

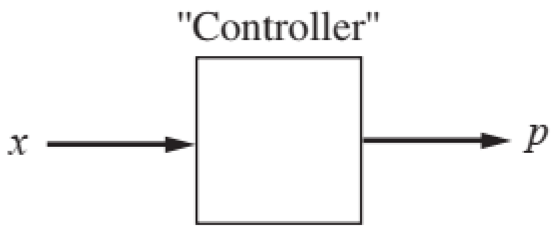
  Control valve (pressure-to-flow rate)

- Thermocouple is used to measure the temperature.
- Signal from the thermocouple is sent to a transducer, which produces a current output in the range of 4 to 20 mA. which is a linear function of the input.
- The output of the transducer enters the controller where it is compared to the set point to produce an error signal.
- The computer/controller converts the error to an output signal in the range of 4 to 20 mA in accordance with the computer control algorithm.
- Output of the computer/controller enters the converter, which produces an output in the range of 3 to 15 psig, as a linear function of the input.
- Finally, the air pressure output of the converter is sent to the top of the control valve, which adjusts the flow of steam to the heat exchanger.
- The external power (120 V) needed for each component. Electricity is needed for the transducer, computer/controller, and converter.
- A source of 20 psig air is also needed for the converter.



- For convenience in describing various control laws (or algorithms) in the next part of this chapter, the transducer, controller, and converter will be lumped into one block,





- This concludes our brief introduction to valves and controllers.
- These transfer functions, especially for controllers, are based on ideal devices that can be only approximated in practice.
- The degree of approximation is sufficiently good to warrant use of these transfer functions to describe the dynamic behavior of controller mechanisms for ordinary design purposes.
- Because the transducer and the converter will be lumped together with the controller for simplicity, the result is that the input will be the measured variable *x* (e.g., temperature and fluid level) and the output will be a pneumatic signal *p.*
- Actually this form (*x* as input and *p* as output) applies to a pneumatic controller.
- For convenience, we will refer to the lumped components as the controller in the following discussion, even though the actual electronic controller is but one of the components.

IDEAL TRANSFER FUNCTIONS

- A pneumatic valve always has some dynamic lag, which means that the stem position does not respond instantaneously to a change in the applied pressure from the controller.
- From experiments conducted on pneumatic valves, it has been found that the relationship between flow and valve-top pressure for a linear valve can often be represented by a first-order transfer function; thus

$$\text{Control valve first-order transfer function} \qquad \frac{Q(s)}{P(s)} = \frac{K_v}{\tau_v s + 1}$$

- where K_v is the steady-state gain, i.e., the constant of proportionality between the steady state flow rate and the valve-top pressure, and τ_v is the time constant of the valve.
- In many practical systems, the time constant of the valve is very small when compared with the time constants of other components of the control system, and the transfer function of the valve can be approximated by a constant.

$$\text{Control valve (fast dynamics) transfer function} \qquad \frac{Q(s)}{P(s)} = K_v$$

- Under these conditions, the valve is said to contribute negligible dynamic lag.
- To justify the approximation of a fast valve by a transfer function, which is simply K_v, consider a first-order valve and a first-order process connected in series.
- The relationship between the air pressure to the valve and the output from the process (perhaps a reactor temperature) is

$$\frac{Y(s)}{P(s)} = \frac{K_v K_P}{(\tau_v s + 1)(\tau_P s + 1)}$$

- For a unit-step change in the valve-top pressure *P*,

$$Y = \frac{1}{s}\frac{K_v K_P}{(\tau_v s + 1)(\tau_P s + 1)}$$

- The inverse of which is

$$Y(t) = K_v K_P\left[1 - \frac{\tau_v \tau_P}{\tau_v - \tau_P}\left(\frac{1}{\tau_P}e^{-t/\tau_v} - \frac{1}{\tau_v}e^{-t/\tau_P}\right)\right]$$

If $\tau_v \ll \tau_P$, this equation is approximately

$$Y(t) = K_v K_P\left(1 - e^{-t/\tau_P}\right)$$

The last expression is the unit-step response of the transfer function

$$\frac{Y(s)}{P(s)} = K_v \frac{K_P}{\tau_P s + 1}$$

- A typical pneumatic valve has a time constant of the order of 1 s.
- Many industrial processes behave as first-order systems or as a series of first-order systems having time constants that may range from a minute to an hour.
- For these systems we have shown that the lag of the valve is negligible, and we will make frequent use of this approximation.

PROPORTIONAL CONTROL

The simplest type of controller is the proportional controller.
(The ON/OFF control is really the simplest, but it is a special case of the proportional controller as we'll see shortly.)
Our goal is to reduce the error between the process output and the set point.
The proportional controller, as we will see, can reduce the error, but cannot eliminate it.
If we can accept some residual error, proportional control may be the proper choice for the situation.

- The proportional controller has only one adjustable parameter, the controller gain.
- The proportional controller produces an output signal

  (pressure in the case of a pneumatic controller, current, or voltage for an electronic controller) that is proportional to the error ε.
- This action may be expressed as

Proportional controller $$p = K_c\varepsilon + p_s$$

where p = output signal from controller, psig or mA

K_c = proportional gain, or sensitivity

ε = error = (set point) − (measured variable)

p_s = a constant, the steady-state output from the controller

- The error ε, which is the difference between the set point and the signal from the measuring element, may be in any suitable units.
- However, the units of the set point and the measured variable must be the same, since the error is the difference between these quantities.

- In a controller having adjustable gain, the value of the gain *Kc* can be varied by entering it into the controller, usually by means of a keypad (or a knob on older equipment).
- The value of p_s is the value of the output signal when ε is zero, and in most controllers p_s can be adjusted to obtain the required output signal when the control system is at steady state and $\varepsilon = 0$.
  we first introduce the deviation
- variable

$$P(t) = K_c \varepsilon(t)$$

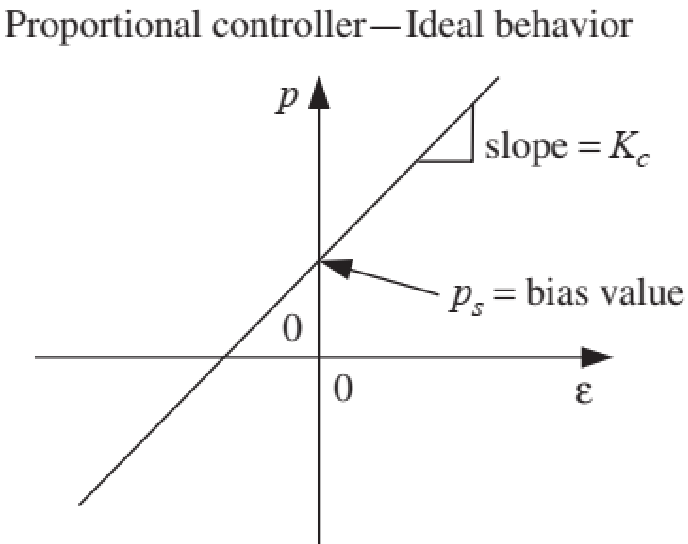
$$P = p - p_s$$

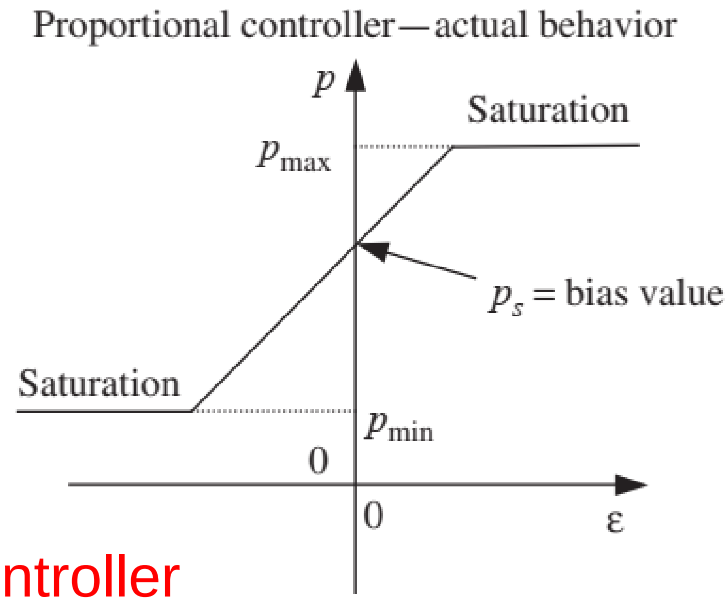
At time t= 0, we assume the error ε_s to be zero. Then ε is already a deviation variable.

$$P(t) = K_c \varepsilon(t)$$

Gives the transfer function of an ideal proportional controller.

Proportional controller transfer function $$\frac{P(s)}{\varepsilon(s)} = K_c$$





The actual behavior of a proportional controller

The controller output will saturate (level out) at p_{max} 15 psig or 20 mA at the upper end and at p_{min} 3 psig or 4 mA at the lower end of the output.

Example 9.1. A pneumatic proportional controller is used in the process shown in Fig. 9–2 to control the cold stream outlet temperature within the range of 60 to 120°F. The controller gain is adjusted so that the output pressure goes from 3 psig (valve fully closed) to 15 psig (valve fully open) as the measured temperature goes from 71 to 75°F with the set point held constant. Find the controller gain K_c.

$$\text{Gain} = \frac{\Delta p}{\Delta \varepsilon} = \frac{15\text{ psig} - 3\text{ psig}}{75°\text{F} - 71°\text{F}} = 3\text{ psi/°F}$$

ON/OFF CONTROL

A special case of proportional control is on/off control.

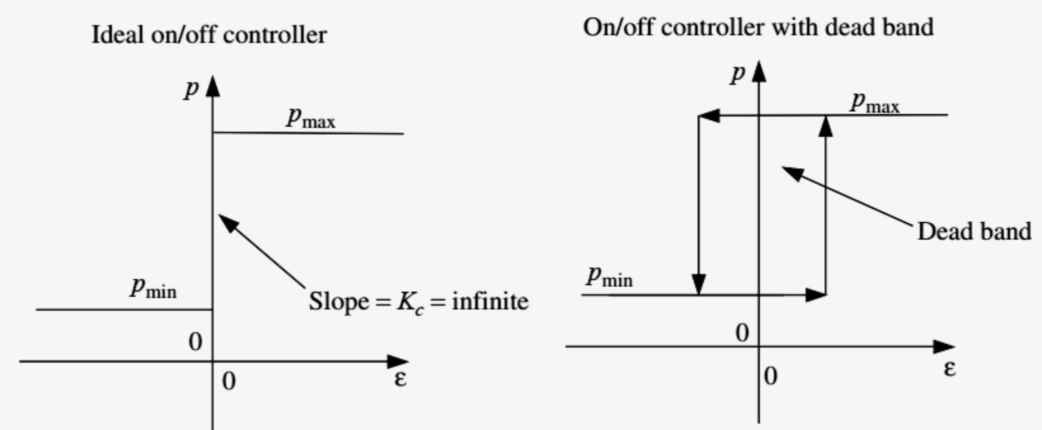
If the gain K_c is made very high, the valve will move from one extreme position to the other if the process deviates only slightly from the set point.

This very sensitive action is called on/off action because the valve is either fully open (on) or fully closed (off); i.e., the valve acts as a switch.

This is a very simple controller and is exemplified by the thermostat used in a home-heating system.

In practice, a dead band is inserted into the controller. With a dead band, the error reaches some finite positive value before the controller "turns on." Conversely, the error must fall to some finite negative value before the controller "turns off."

Expanding the width of the dead band makes the controller less sensitive to noise and prevents the phenomenon of *chattering,* where the controller will rapidly cycle on and off as the error fluctuates about zero. Chattering is detrimental to equipment performance.



PROPORTIONAL-INTEGRAL (PI) CONTROL

If we cannot tolerate any residual error, we will have to introduce an additional control mode: integral control.

If we add integral control to our proportional controller, we have what is termed PI, or proportional-integral control.

The integral mode ultimately drives the error to zero.

This controller has two adjustable parameters for which we select values, the gain and the integral time.

Thus it is a bit more complicated than a proportional controller, but in exchange for the additional complexity, we reap the advantage of no error at steady state. PI control is described by the relationship

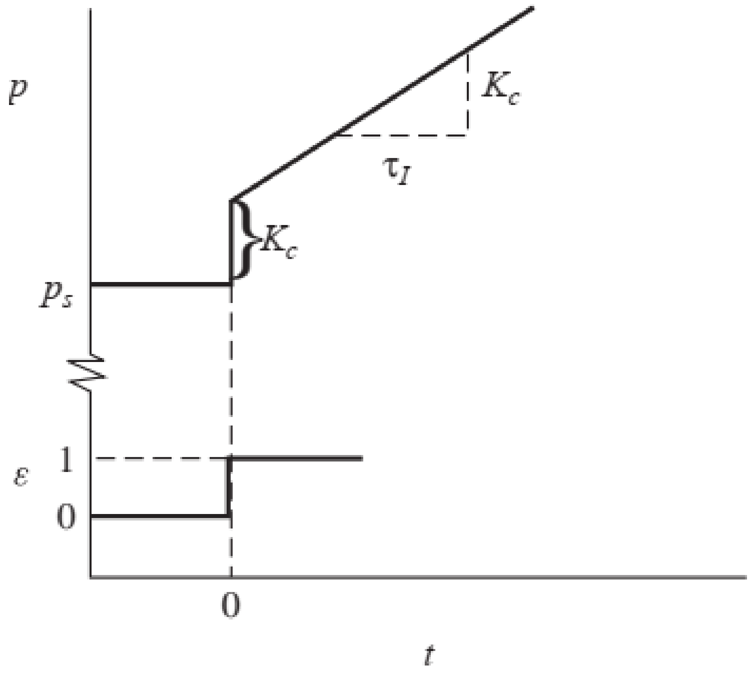
Proportional-integral controller

$$p = K_c\varepsilon + \frac{K_c}{\tau_I}\int_0^t \varepsilon dt + p_s$$

where K_c = proportional gain
τ_I = integral time, min
p_s = constant (the bias value)

In this case, we have added to the proportional action term *Kc* ε another term that is proportional to the integral of the error.
The values of *Kc* and t_I are both adjustable.
To visualize the response of this controller, consider the response to a unit-step change in error.
This unit-step response is most directly obtained by inserting ε= 1.

$$p(t) = K_c + \frac{K_c}{\tau_I} t + p_s$$



To obtain the transfer function of the deviation variable $P = p - p_s$ into Eq. and then take the transform to obtain

Proportional-integral controller transfer function

$$\frac{P(s)}{\varepsilon(s)} = K_c\left(1 + \frac{1}{\tau_I s}\right)$$

Some manufacturers prefer to use the term *reset rate*, which is defined as the reciprocal of t_I.

The calibration of the proportional and integral action is often checked by observing the jump and slope of a step response

PROPORTIONAL-DERIVATIVE (PD) CONTROL

Derivative control is another mode that can be added to our proportional or proportional-integral controllers.

It acts upon the derivative of the error, so it is most active when the error is *changing* rapidly.

It serves to reduce process oscillations.

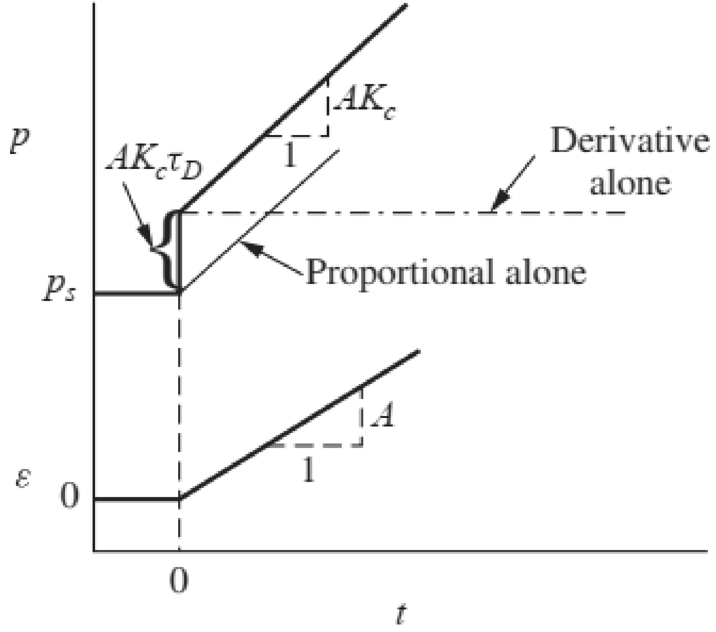
- This mode of control may be represented by

Proportional-derivative controller $$p = K_c\varepsilon + K_c\tau_D \frac{d\varepsilon}{dt} + p_s$$

where K_c = proportional gain
τ_D = derivative time, min
p_s = constant (bias value)

In this case, we have added to the proportional term another term $K_c\ \tau_D\ d\varepsilon/dt$, which is proportional to the derivative of the error. The values of K_c and τ_D are both adjustable.

Other terms that are used to describe the derivative action are *rate control* and *anticipatory control.*



This response is obtained by introducing the linear function

$e(t) = At$

$$p(t) = AK_ct + AK_c\tau_D + p_s$$

Notice that p changes suddenly by an amount $AK_c t_D$ as a result of the derivative action and then changes linearly at a rate AK_c.

The effect of derivative action in this case is to anticipate the linear change in error by adding output $AK_c t_D$ to the proportional action.

The controller is taking preemptive action to counter the anticipated change in the error that it predicted from the slope of the error versus time curve.

Introduce the deviation variable $P = p - p_s$ and then take the transform to obtain

Proportional-derivative controller transfer function	$\frac{P(s)}{\varepsilon(s)} = K_c(1 + \tau_D s)$