Related Commercial Resources

CHAPTER 7

FUNDAMENTALS OF CONTROL

AUTOMATIC HVAC control systems are designed to maintain temperature, humidity, pressure, energy use, power, lighting levels, and safe levels of indoor contaminants. Automatic control primarily modulates actuators; stages modes of action; or sequences the mechanical and electrical equipment on and off to satisfy load requirements, provide safe equipment operation, and maintain safe building contaminant levels. Automatic control systems can use digital, pneumatic, mechanical, electrical, and electronic control devices. Human intervention often involves scheduling equipment operation and adjusting control set points; but also includes tracking trends and programming control logic algorithms to fulfill building needs.

This chapter focuses on the fundamental concepts and devices normally used by a control system designer. It covers (1) control fundamentals, including terminology; (2) types of control components; (3) methods of connecting components to form various individual control loops, subsystems, or networks; and (4) commissioning and operation. Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* discusses the design of controls for specific HVAC applications.

TERMINOLOGY

A **closed loop** or **feedback** control measures actual changes in the controlled variable and actuates the controlled device to bring about a change. The corrective action may continue until the variable is brought to a desired value within the design limitations of the controller. This arrangement of having the controller respond to the value of the controlled variable is known as feedback. Figure 1 shows an example of feedback control.

An **open-loop** control does not have a direct link between the value of the controlled variable and the controller. An open-loop control anticipates the effect of an external variable on the system and adjusts the set point to avoid excessive offset. An example is an outdoor thermostat arranged to control heat to a building in proportion to the calculated load caused by changes in outdoor temperature. In essence, the designer presumes a fixed relationship between outside air temperature and the building's heat requirement, and specifies control action based on the outdoor air temperature. The actual space temperature has no effect on this controller. Because there is no feedback on the controlled variable (space temperature), the control is an open loop.

Every **closed loop** must contain a sensor, a controller, and a controlled device. Figure 1 illustrates the components of the typical control loop. The **sensor** measures the controlled variable and transmits to the controller a signal (pneumatic, electric, or electronic) having a pressure, voltage, or current value related by a known function to the value of the variable being measured. The **controller** compares this value with the set point and signals to the controlled device for corrective action. A controller can be hardware or software. A hardware controller is an analog device (e.g., thermostat, humidistat, pressure control) that continuously receives and acts on data. A software controller is a digital device (e.g., digital algorithm) that receives and acts on data on a sample-rate basis. The **controlled device** is typically a valve, damper, heating element, or variable-speed drive.

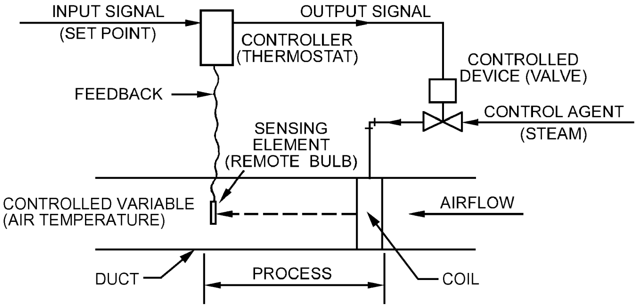

Fig. 1 Example of Feedback Control: Discharge Air Temperature Control

The **set point** is the desired value of the controlled variable. The controller seeks to maintain this set point. The controlled device reacts to signals from the controller to vary the control agent.

The **control agent** is the medium manipulated by the controlled device. It may be air or gas flowing through a damper; gas, steam, or water flowing through a valve; or an electric current.

The **process** is the HVAC apparatus being controlled, such as a coil, fan, or humidifier. It reacts to the control agent's output and effects the change in the controlled variable.

The **controlled variable** is the temperature, humidity, pressure, or other condition being controlled.

A control loop can be represented in the form of a **block diagram**, in which each component is modeled and represented in its own block. Figure 2 is a block diagram of the control loop shown in Figure 1. Information flow from one component to the next is shown by lines between the blocks. The figure shows the set point being compared to the controlled variable. The difference is the **error**. If the error persists, it may be called offset drift, deviation, droop, or steady-state error. The error is fed into the controller, which sends a control signal to the controlled device (in this case, a valve that can change the amount of steam flow through the coil of Figure 1). The amount of steam flow is the input to the next block, which represents

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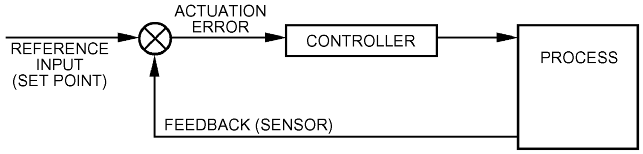


Fig. 2 Block Diagram of Discharge Air Temperature Control

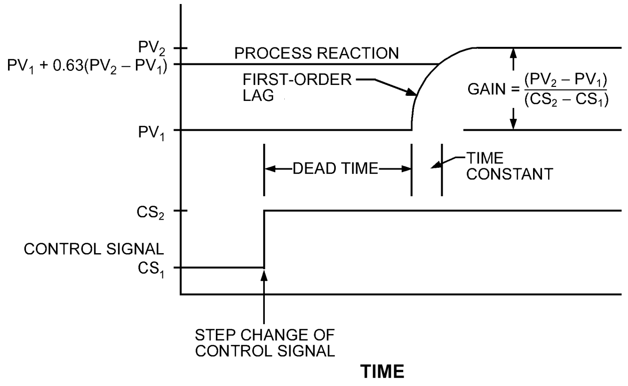


Fig. 3 Process Subjected to Step Input

the process. From the process block comes the controlled variable, which is temperature. The controlled variable is sensed by the sensing element and fed to the controller as feedback, completing the loop.

Control loop performance is greatly affected by time lags, which are delay periods associated with seeing a control agent change reflected in the desired end-point condition. Time lags can cause control and modeling problems and should be understood and evaluated carefully. There are two types of time lags: first-order lags and dead time.

First-order lags involve the time it takes for the change to be absorbed by the system. If heat is supplied to a cold room, the room heats up gradually, even though heat may be applied at the maximum rate. The **time constant** is the unit of measure used to describe first-order lags and it is defined as the time it takes for the controlled variable of a first-order, linear system to reach 63.2% of its final value when a step change in the input occurs. Components with small time constants alter their output rapidly to reflect changes in the input; components with a larger time constant are sluggish in responding to input changes.

Dead time (or time lag) is the time from when a change in the controller output is made to when the controlled variable exhibits a measurable response. Dead time can occur in the control loop of Figure 1 because of the transportation time of the air from the coil to the space. After a coil temperature changes, there is dead time while the supply air travels the distribution system and finally reaches the sensor in the space. The mass of air in the space further delays the coil temperature change's effect on the controlled variable (space temperature). Dead time can also be caused by a slow sensor or a time lag in the signal from the controller when it first begins to affect the output of the process. Dead time is most often associated with the time it takes to transport the media changed by the control agent from one place to another. Dead time may also be inadvertently added to a control loop by a controller with an excessive scan time. If the dead time is small, it may be ignored in the control system model; if it is significant, it must be considered.

Figure 1 depicts the mechanisms that create both first-order and dead-time lags, and Figure 3 shows the effect related to time. Dead time is the time it takes warmer air resulting from a higher set point to reach the space, followed by the first-order lag created by the wall on which the thermostat is mounted, and that of the temperature sensor (all of which warm gradually rather than all at once). The control loop must be tuned to account for the combined effect of each time lag. Note that, in most HVAC systems, the first-order lag element predominates.

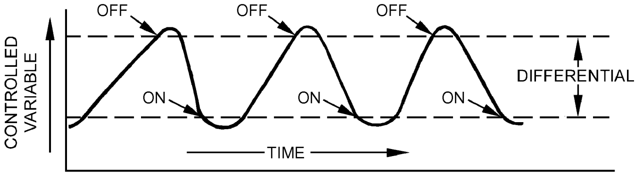


Fig. 4 Two-Position Control

The **gain** of a transfer function is the amount the output of the component changes for a given change of input under steady-state conditions. If the element (valve, damper, and/or temperature/pressure differential) is linear, its gain remains constant. However, many control components are nonlinear and have gains that depend on the operating conditions. Figure 3 shows the response of the first-order-plus-dead-time process to a step change of the input signal. Note that the process shows no reaction during dead time, followed by a response that resembles a first-order exponential.

TYPES OF CONTROL ACTION

Control loops can be classified by the adjustability of the controlled device. A **two-position** controlled device has two operating states (e.g., open and closed), whereas a **modulating** controlled device has a continuous range of operating states (e.g., 0 to 100% open).

Two-Position Action

The control device shown in Figure 4 can be positioned only to a maximum or minimum state (i.e., on or off). Because two-position control is simple and inexpensive, it is used extensively for both industrial and commercial control. A typical home thermostat that starts and stops a furnace is an example.

Controller differential, as it applies to two-position control action, is the difference between a setting at which the controller operates to one position and a setting at which it operates to the other. Thermostat ratings usually refer to the differential (in degrees) that becomes apparent by raising and lowering the dial setting. This differential is known as the **manual differential** of the thermostat. When the same thermostat is applied to an operating system, the total change in temperature that occurs between a "turn-on" state and a "turn-off" state is usually different from the mechanical differential. The **operating differential** may be greater because of thermostat lag or hysteresis, or less because of heating or cooling anticipators built into the thermostat.

Anticipation Applied to Two-Position Action. This common variation of strictly two-position action is often used on room thermostats to reduce the operating differential. In heating thermostats, a heater element in the thermostat is energized during *on* periods, thus shortening the *on* time because the heater warms the thermostat (**heat anticipation**). The same anticipation action can be obtained in cooling thermostats by energizing a heater thermostat at *off* periods. In both cases, the percentage of *on* time is varied in proportion to the load, and the total cycle time remains relatively constant.

Modulating Control

With modulating control, the controller's output of the controller can vary over its entire range. The following terms are used to describe this type of control:

- **Throttling range** is the amount of change in the controlled variable required to cause the controller to move the controlled device from one extreme to the other. It can be adjusted to meet job requirements. The throttling range is inversely proportional to proportional gain.

- **Control point** is the actual value of the controlled variable at which the instrument is controlling. It varies within the controller's throttling range and changes with changing load on the system and other variables.
- **Offset**, or error signal, is the difference between the set point and actual control point under stable conditions. This is sometimes called drift, deviation, droop, or steady-state error.

In each of the following examples of modulating control, there is a set of parameters that quantifies the controller's response. The values of these parameters affect the control loop's speed, stability, and accuracy. In every case, control loop performance depends on matching (or **tuning**) the parameter values to the characteristics of the system under control.

Proportional Control. In proportional control, the controlled device is positioned proportionally in response to changes in the controlled variable (Figure 5). A proportional controller can be described mathematically by

$$V_p = K_p e + V_o \tag{1}$$

where

V_p = controller output
K_p = proportional gain parameter (inversely proportional to throttling range)
e = error signal or offset
V_o = offset adjustment parameter

The controller output is proportional to the difference between the sensed value, the controlled variable, and its set point. The controlled device is normally adjusted to be in the middle of its control range at set point by using an offset adjustment. This control is similar to that shown in Figure 5.

Proportional plus Integral (PI) Control. PI control improves on simple proportional control by adding another component to the control action that eliminates the offset typical of proportional control (Figure 6). Reset action may be described by

$$V_p = K_p e + K_i \int e \, d\theta + V_o \tag{2}$$

where

K_i = integral gain parameter
θ = time

The second term in Equation (2) implies that the longer error *e* exists, the more the controller output changes in attempting to eliminate the error. Proper selection of proportional and integral gain constants increases stability and eliminates offset, giving greater control accuracy. PI control can also improve energy efficiency in applications such as VAV fan control, chiller control, and hot- and cold-deck control of an air handler because it reduces steady-state error.

Proportional-Integral-Derivative (PID) Control. This is PI control with a derivative term added to the controller. It varies with the value of the derivative of the error. The equation for PID control is

$$V_p = K_p e + K_i \int e \, d\theta + K_d \frac{de}{d\theta} + V_o \tag{3}$$

where

K_d = derivative gain parameter of controller
$de/d\theta$ = time derivative of error

Adding the derivative term gives some anticipatory action to the controller, which results in a faster response and greater stability. However, the derivative term also makes the controller more sensitive to noisy signals and harder to tune than a PI controller. Most HVAC control loops perform satisfactorily with PI control alone.

Adaptive Control. An adaptive controller adjusts the parameters that define its response as the dynamic characteristics of the process change. If the controller is PID-based, then it adjusts feedback gains. An adaptive controller may be based on other feedback rules. The key is that it adjusts its parameters to match the characteristics of the process. When the process changes, the tuning parameters change to match it. Adaptive control is applied in HVAC systems because normal variations in the operating conditions affect the characteristics relevant to tuning. For instance, the extent to which zone dampers are open or closed in a VAV system affects the way duct pressure responds to fan speed, and entering fluid temperatures at a coil affect the way the leaving temperature responds to the valve position.

Fuzzy Logic. This type of control offers an alternative to traditional control algorithms. A fuzzy logic controller uses a series of "if-then" rules that emulates the way a human operator might control the process. Examples of fuzzy logic might include

- IF room temperature is high AND temperature is decreasing, THEN increase cooling a little.
- IF room temperature is high AND temperature is increasing, THEN increase cooling a lot.

The designer of a fuzzy logic controller must first define the rules and then define terms such as *high*, *increasing*, *decreasing*, *a lot*, and *a little*. Room temperature, for instance, might be mapped into a series of functions that include *very low*, *low*, *OK*, *high*, and *very high*. The "fuzzy" element is introduced when the functions overlap and the room temperature is, for example, 70% high and 30% OK. In this case, multiple rules are combined to determine the appropriate control action.

Combinations of Two-Position and Modulating

Some control loops include two-position components in a system that exhibits nearly modulating response.

Timed Two-Position Control. This cycles a two-position heating or cooling element on and off quickly enough that the effect on the controlled temperature approximates a modulating device. In this case, a controller may adjust the duty cycle ("on-time" as a percentage of "cycle-time") as a modulating control variable. For example, an element may be turned on for two minutes and off

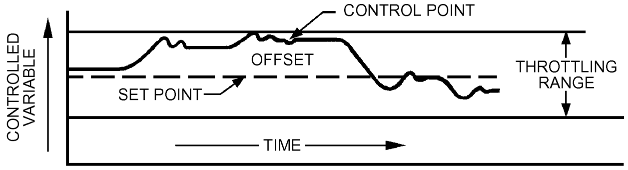


Fig. 5 Proportional Control Showing Variations in Controlled Variable as Load Changes

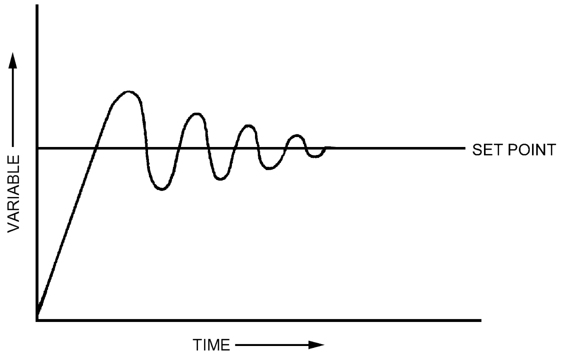


Fig. 6 Proportional plus Integral (PI) Control

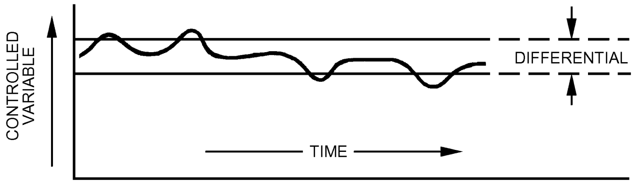


Fig. 7 Floating Control Showing Variations in Controlled Variable as Load Changes

for one minute when the deviation from set point is 3°F. Timed two-position action combines a modulating controller with a two-position controlled device.

Floating Control. This combines a modulating controlled device with a pair of two-position outputs. The controlled device has a continuous operating range, but the actuators that move it only turn on and off. The controller selects one of three operations: moving the controlled device toward its open position, moving it toward its closed position, or leaving the device in its current position. Control is accomplished by applying a pair of two-position contacts with a selected gap between their set points (Figure 7). Generally, a neutral zone between the two positions allows the controlled device to stop at any position when the controlled variable is within the differential of the controller. When the controlled variable falls outside the differential of the controller, the controller moves the controlled device in the proper direction. To function properly, the sensing element must react faster than the actuator drive time. If not, the control functions the same as a two-position control. When applied with a digital controller, floating-point control is also referred to as **tri-state control**.

Incremental Control. This variation of floating control varies the pulse action to open or close an actuator, depending on how close the controlled variable is to the set point. As the controlled variable comes close to the set point, the pulses become shorter. This allows closer control using floating motor actuators. When applied with a digital controller, incremental control is also referred to as **pulse-width-modulation (PWM) control**.

CLASSIFICATION BY ENERGY SOURCE

Control components may be classified according to the primary source of energy as follows:

- **Pneumatic components** use compressed air, usually at a pressure of 15 to 20 psig, as an energy source. The air is generally supplied to the controller, which regulates the pressure supplied to the controlled device.
- **Electric components** use electrical energy, either low or line voltage, as the energy source. The controller regulates electrical energy supplied to the controlled device. Controlled devices in this category include relays and electromechanical, electromagnetic, and solid-state regulating devices.

  Electronic components include signal conditioning, modulation, and amplification in their operation. Electronic systems use analog circuitry, rather than digital logic, to implement their control functions.

  A **digital electronic controller** receives analog electronic signals from the sensors, converts the electronic signals to digital values, and performs mathematical operations on these values inside a microprocessor. Output from the digital controller takes the form of a digital value, which is then converted to an electronic signal to operate the actuator. The digital controller must sample its data because the microprocessor requires time for operations other than reading data. If the sampling interval for the digital controller is properly chosen to avoid second- and third-order harmonics, there will be no significant degradation in control performance from sampling.
- **Self-powered components** apply the power of the measured system to induce the necessary corrective action. The measuring system derives its energy from the process under control, without any auxiliary source of energy. Temperature changes at the sensor result in pressure or volume changes of the enclosed media that are transmitted directly to the operating device of the valve or damper. A component using a thermopile in a pilot flame to generate electrical energy is also self-powered.

This method of classification can be extended to individual control loops and to complete control systems. For example, the room temperature control for a particular room that includes a pneumatic room thermostat and a pneumatically actuated reheat coil would be referred to as a pneumatic control loop. Many control systems use a combination of control components and are called **hybrid** systems.

Computers for Automatic Control

Computers perform the control functions in direct digital control (DDC) systems. Uses range from personal computers used as operator interfaces for DDC systems to embedded program microprocessors used to control variable air volume boxes, fan-coil units, heat pumps, and other terminal HVAC equipment. Other uses include primary HVAC equipment programmable controllers, distributed network controllers, and servers used to store DDC system trend data. Chapter 39 of the 2007 *ASHRAE Handbook—HVAC Applications* covers computer components and HVAC computer applications more extensively.

CONTROL COMPONENTS

CONTROLLED DEVICES

A control device is the component of a control loop used to vary the input (controlled variable). Both **valves** and **dampers** perform essentially the same function and must be properly sized and selected for the particular application. The control link to the valve or damper is called an **actuator** or **operator**, and uses electricity, compressed air, hydraulic fluid, or some other means to power the motion of the valve stem or damper linkage through its operating range. For additional information, see Chapter 36.

Valves

An automatic valve is designed to control the flow of steam, water, gas, or other fluids. It can be considered a variable orifice positioned by an actuator in response to impulses or signals from the controller. It may be equipped with either a throttling plug, V-port, or rotating ball specially designed to provide a desired flow characteristic.

Types of automatic valves include the following:

A **single-seated valve** (Figure 8A) is designed for tight shutoff. Appropriate disk materials for various pressures and media are used.

A **double-seated** or **balanced valve** (Figure 8B) is designed so that the media pressure acting against the valve disk is essentially balanced, reducing the actuator force required. It is widely used where fluid pressure is too high to allow a single-seated valve to close or to modulate properly. It is not usually used where tight shutoff is required.

A **three-way mixing valve** (Figure 9A) has two inlet connections and one outlet connection and a double-faced disk operating between two seats. It is used to mix two fluids entering through the two inlet connections and leaving through the common outlet, according to the position of the valve stem and disk.

A **three-way diverting valve** (Figure 9B) has one inlet connection and two outlet connections, and two separate disks and seats. It is used to divert flow to either of the outlets or to proportion the flow

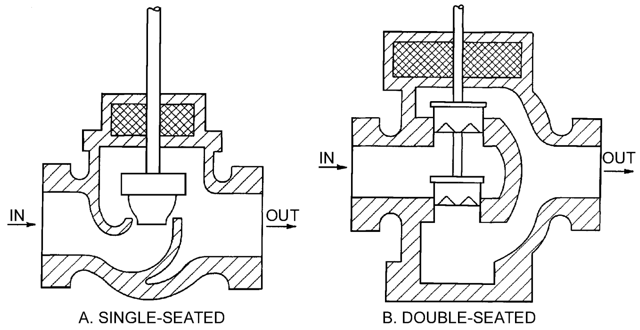


Fig. 8 Typical Single- and Double-Seated Two-Way Valves

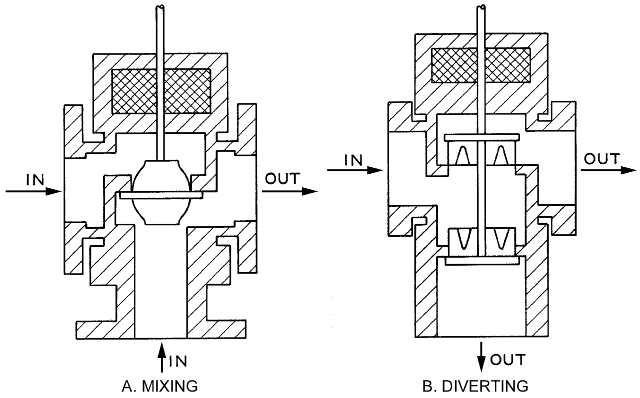


Fig. 9 Typical Three-Way Mixing and Diverting Valves

to both outlets. Three-way diverting valves are more expensive and have more complex applications, and generally are not used in typical HVAC systems.

A **butterfly valve** consists of a heavy ring enclosing a disk that rotates on an axis at or near its center and is similar to a round single-blade damper. In principle, the disk seats against a ring machined within the body or a resilient liner in the body. Two butterfly valves can be used together to act like a three-way valve for mixing or diverting. Butterfly valves are designed for two-position action. In condenser water applications with pipe sizes 4 in. and above, butterfly valves are often used in modulating positions because they are less expensive than globe-style valves (see Chapter 46 of the 2008 *ASHRAE Handbook—HVAC Systems and Equipment* for information on globe valves).

A **ball valve** consists of a ball with a hole drilled through it, rotating in a valve body. Ball valves are increasingly popular because of their low cost and high close-off ratings. Features that provide flow characteristics similar to globe valves are available.

Pressure-independent valves are control valves with integral pressure regulators. This allows the valve to respond in a more linear way, because pressure is constant.

Flow Characteristics. Valve performance is expressed in terms of its flow characteristics as it operates through its stroke, based on a constant pressure drop. Three common characteristics are shown in Figure 10 and are defined as follows:

- **Quick opening.** Maximum flow is approached rapidly as the device begins to open.
- **Linear.** Opening and flow are related in direct proportion.
- **Equal percentage.** Each equal increment of opening increases flow by an equal percentage over the previous value.

Because pressure drop across a valve seldom remains constant as its opening changes, actual performance usually deviates from the published characteristic curve. The magnitude of deviation is determined by the overall design. For example, in a system arranged so that control valves or dampers can shut off all flow, pressure drop across a controlled device increases from a minimum at design conditions to total pressure drop at no flow. Figure 11 shows the extent of resulting deviations for a valve or damper designed with a linear characteristic, when selection is based on various percentages of total system pressure drop. To allow for adequate control by valve or damper, design pressure drop should be a reasonably large percentage of total system pressure drop, or the system should be designed and controlled so that pressure drop remains relatively constant.

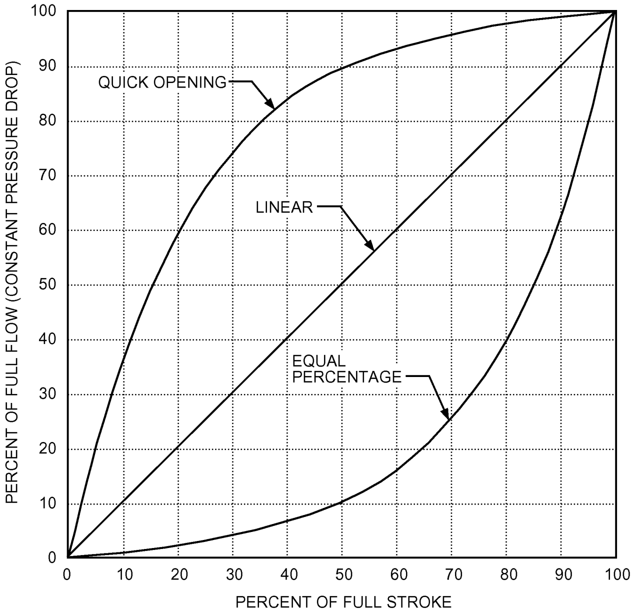


Fig. 10 Typical Flow Characteristics of Valves

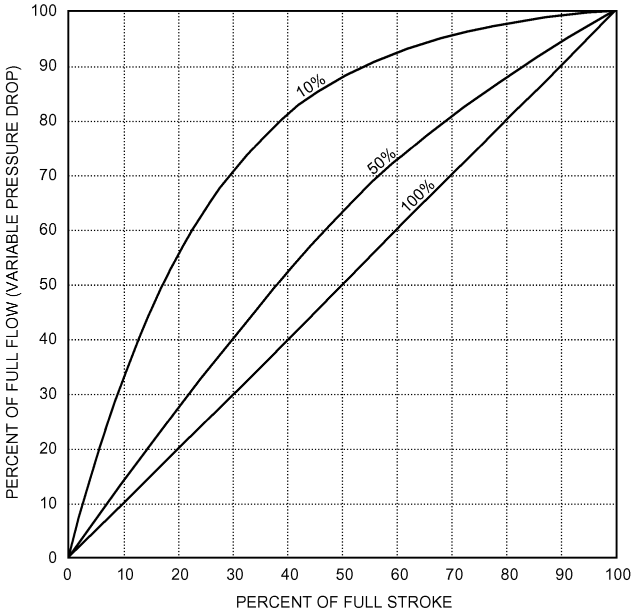


Fig. 11 Typical Performance Curves for Linear Devices at Various Percentages of Total System Pressure Drop

Selection and Sizing. Higher pressure drops for controlled devices are obtained by using smaller sizes, with a possible increase in size of other equipment in the system. Sizing control valves is discussed in Chapter 46 of the 2008 *ASHRAE Handbook—HVAC Systems and Equipment*.

Steam Valves. Steam-to-water and steam-to-air heat exchangers are typically controlled by regulating steam flow using a two-way throttling valve. One-pipe steam systems require a line-size, two-position valve for proper condensate drainage and steam flow; two-pipe steam systems can be controlled by two-position or modulating (throttling) valves. Maximum pressure drop for steam valves is a function of operating pressure and cannot be exceeded.

Water Valves. Valves for water service may be two- or three-way and two-position or proportional. Proportional valves are used most often, but two-position valves are not unusual and are sometimes essential. Variable-flow systems are designed to keep the pressure differential constant from supply to return. For valve selection, it is safer to assume that the pressure drop across the valve increases as it modulates from fully open to fully closed.

Equal-percentage valves provide better control at part load, particularly in hot-water coils where the coil's heat output is not linearly related to flow. As flow reduces, more heat is transferred from each unit of water, counteracting the reduction in flow. Equal-percentage valves are used to provide linear heat transfer from the coil with respect to the control signal.

For information on control valve sizing and selection, see Chapter 46 of the 2008 *ASHRAE Handbook—HVAC Systems and Equipment*.

Actuators. Valve actuators include the following general types:

- A **pneumatic valve actuator** consists of a spring-opposed, flexible diaphragm or bellows attached to the valve stem. An increase in air pressure above the minimum point of the spring range compresses the spring and simultaneously moves the valve stem. Springs of various pressure ranges can sequence the operation of two or more devices, if properly selected or adjusted. For example, a chilled-water valve actuator may modulate the valve from fully closed to fully open over a spring range of 8 to 13 psig, whereas a sequenced steam valve may actuate from 3 to 8 psig.

  Two-position pneumatic control is accomplished using a two-position pneumatic relay to apply either full air pressure or no pressure to the valve actuator. Pneumatic valves and valves with spring-return electric actuators can be classified as normally open or normally closed.

  A **normally open valve** assumes an open position, providing full flow, when all actuating force is removed.

  A **normally closed valve** assumes a closed position, stopping flow, when all actuating force is removed.
- **Double-acting** or **springless pneumatic valve actuators**, which use two opposed diaphragms or two sides of a single diaphragm, are generally limited to special applications involving large valves or high fluid pressure.
- An **electric-hydraulic valve actuator** is similar to a pneumatic one, except that it uses an incompressible fluid circulated by an internal electric pump.
- A **solenoid** consists of a magnetic coil operating a movable plunger. Most are for two-position operation, but modulating solenoid valves are available with a pressure equalization bellows or piston to achieve modulation. Solenoid valves are generally limited to relatively small sizes (up to 4 in.).
- An **electric motor** actuates the valve stem through a gear train and linkage. Electric motor actuators are classified in the following three types:

  Unidirectional, for two-position operation. The valve opens during one half-revolution of the output shaft and closes during the other half-revolution. Once started, it continues until the half-revolution is completed, regardless of subsequent action by the controller. Limit switches in the actuator stop the motor at the end of each stroke. If the controller has been satisfied during this interval, the actuator continues to the other position.

  Spring-return, for two-position operation (energy drives the valve to one position and a spring returns the valve to its normal position) or for modulating operation (energy drives the valve to a variable position and a spring returns the valve to an open or closed position upon a signal or power failure).

  Reversible, for floating and proportional operation. The motor can run in either direction and can stop in any position. It is sometimes equipped with a return spring. In proportional-control applications, a feedback potentiometer for rebalancing the control circuit is also driven by the motor.

Dampers

Damper leakage is a concern, particularly where tight shutoff is necessary to significantly reduce energy consumption. Also, outdoor air dampers in cold climates must close tightly to prevent coils and pipes from freezing. Low-leakage dampers cost more and require larger actuators because of friction of the seals in the closed position; however, the energy savings pays for the extra cost.

Types and Characteristics. Automatic dampers are used in air conditioning and ventilation to control airflow. They may be used (1) to modulate control to maintain a controlled variable, such as mixed air temperature or supply air duct static pressure; or (2) for two-position control to initiate operation, such as opening minimum outside air dampers when a fan is started.

Multiblade dampers are typically available in two arrangements: parallel-blade and opposed-blade (Figure 12), although combinations of the two are manufactured. They are used to control flow through large openings typical of those in air handlers. Both types are adequate for two-position control.

When dampers are applied in modulating control loops, a nonlinear relationship between flow and stroke can lead to difficulties in tuning a control loop for performance. Nonlinearity is expressed as variation in the slope of the flow versus stroke curve. Perfect linearity is not required: if slope varies throughout the range of required flow by less than a factor of 2 from the slope at the point where the loop is tuned, nonlinearity is not likely to disrupt performance.

Parallel blades are used for modulating control when the pressure drop of the damper is about 25% or more of the pressure in a subsystem (Figure 13A). **Opposed-blade dampers** are preferable for modulating control when the damper is about 15% or less of the pressure drop in a subsystem (Figure 13B). A subsystem is defined as a portion of the duct system between two relatively constant pressure points (e.g., the return air section between the mixed air and

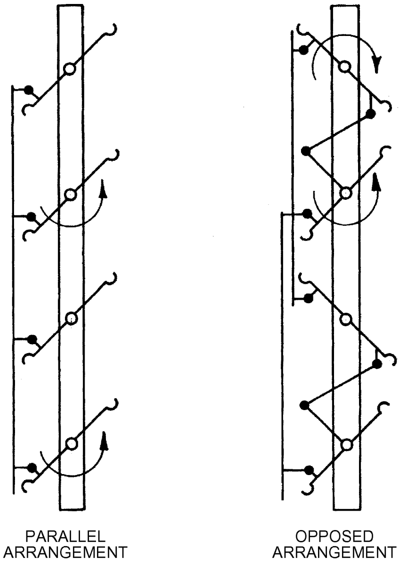
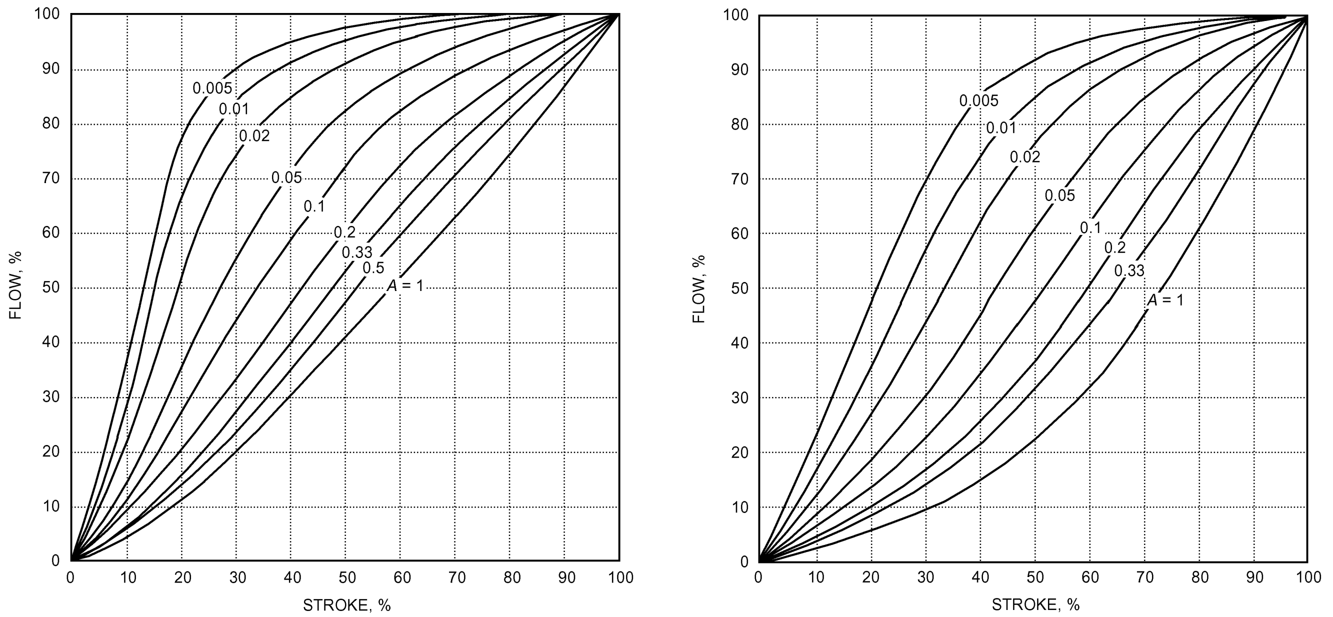
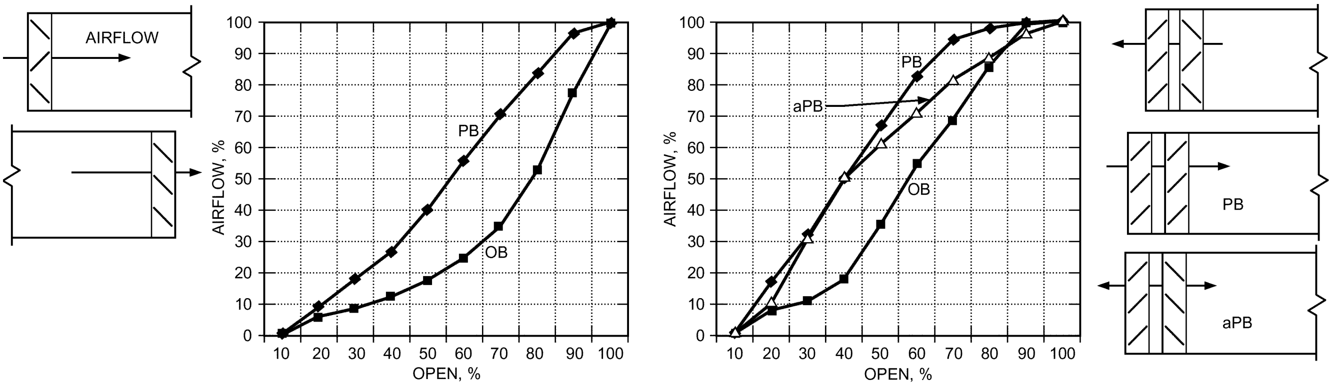


Fig. 12 Typical Multiblade Dampers



(A) PARALLEL-BLADE (B) OPPOSED-BLADE

Fig. 13 Characteristic Curves of Installed Dampers in an AMCA 5.3 Geometry



A. AMCA 5.1 AND 5.2 B. LOUVERED ENTRY AND EXITS

Fig. 14 Inherent Curves for Partially Ducted and Louvered Dampers (RP-1157)

Based on data in van Becelaere et al. (2004)

return plenum tee). A combination may be considered between 15 and 25% damper drop. **Single-blade dampers** are typically used for flow control at the zone.

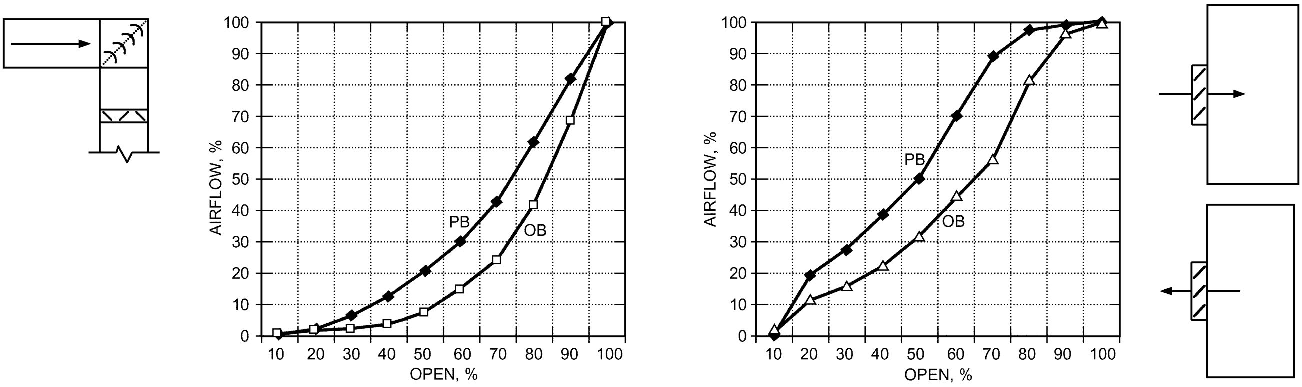
In Figure 13, *A* is **authority**, which is the ratio of the pressure drop across the fully open damper at design flow to the total subsystem pressure drop, including fully open control damper pressure drop**.** The curves here are typical for ducted applications. The Air Movement and Control Association (AMCA 2007) defined a number of geometric arrangements of dampers for testing pressure losses. The curves in Figure 13 are those of an AMCA 5.3 geometry, which is a fully ducted arrangement with long sections of duct before and after a damper. Other geometric applications, such as plenum or wall-mounted dampers, exhibit different response curves (van Becelaere et al. 2004).

Figure 14 shows four applications with parallel-blade (PB) and opposed-blade (OB) as well as an “anti-PB” arrangement. The response curves are not like those of the AMCA 5.3 ducted application. These are “inherent” curves, where pressure drop across a damper is held constant as the damper rotates (so it has 100% authority). In real applications, the authority is lower (higher losses of other system components besides the damper). As system pressure losses increase, the curves move up. Note that PB dampers are significantly above linear in most cases.

Figure 15 shows three more applications with PB and OB dampers. The ducted damper has some disturbance and pressure loss ahead of it, to simulate a more realistic situation than those of AMCA 5.3. Nevertheless, the response curves are similar to AMCA 5.3. The plenum entry dampers show irregular results. Again, these are inherent curves, and lower authority causes the curves to move up toward more flow at smaller angles.

The curves shown here are typical, but do not represent every scenario. Thousands of installation variations exist, and slight variations in response always occur. For additional application examples and greater detail, see ASHRAE research project RP-1157 (van Becelaere et al. 2004).

Application. Dampers require engineering to achieve defined goals. A common application is a flow control damper, which modulates airflow. The curves in Figure 13 can be used to pick a damper with a pressure drop and authority that provides near-linear response. Another common application is economizer outdoor air, return air,



A. DUCTED AFTER ELBOW

B. PLENUM ENTRY AND EXITS

Fig. 15 Inherent Curves for Ducted and Plenum-Mounted Dampers (RP-1157)
Based on data in van Becelaere et al. (2004)

and exhaust air dampers. Selection of these dampers depends on the system design, as discussed in ASHRAE *Guideline* 16-2003.

Actuators. Either electricity or compressed air is used to actuate dampers.

Pneumatic damper actuators are similar to pneumatic valve actuators, except that they have a longer stroke or the stroke is increased by a multiplying lever. Increasing air pressure produces a linear shaft motion, which, through a linkage, moves the crank arm to open or close the dampers. Releasing air pressure allows a spring to return the actuator. Double-acting actuators without springs are available also.

Electric damper actuators can be proportional or two-position. They can be spring-return or non-spring. The simplest form of control is a floating three-point controller, which causes contact closures to drive the motor clockwise or counterclockwise. In addition, a variety of standard electronic signals from electronic controllers or DDC systems, such as 4 to 20 mA or 0 to 10 V (dc), can be used to control proportionally actuated dampers.

Most modern actuators are electronic and use more sophisticated methods of control and operation. They are inherently positive-positioning and may have communications capabilities similar to process quality actuators.

A two-position spring-return actuator moves in one direction when power is applied to its internal windings; when no power is present, the actuator returns (via spring force) to its normal position. Depending on how the actuator is connected, this action opens or closes the dampers. A proportional actuator may also have spring-return action.

Mounting. Damper actuators are mounted in different ways, depending on the size and accessibility of the damper, and the power required to move the damper. The most common method of mounting electric actuators is directly over the damper shaft with no external linkage. It is not recommended, but actuators can also be mounted in the airflow on the damper frame and be linked directly to a damper blade, or mounted outside the duct and connected to a crank arm attached to a shaft extension of one of the blades. Large dampers may require two or more actuators, which are usually mounted at separate points on the damper. An alternative is to install the damper in two or more sections, each section being controlled by a single damper actuator; however, proper flow control is easier with a single proportional damper. Positive positioners may be required for proper sequencing. A small damper with a two-position spring-return actuator may be used for minimum outside flow, with a large damper being independently controlled for economy-cycle cooling.

Positive (Pilot) Positioners

A pneumatic actuator may not respond quickly or accurately enough to small changes in control pressure caused by friction in the actuator or load, or to changing load conditions such as wind acting on a damper blade. Where accurate positioning of a modulating damper or valve in response to load is required, positive positioners should be used. A positive positioner provides up to full supply control air pressure to the actuator for any change in position required by the controller. A positive positioner provides finite and repeatable positioning change and allows adjustment of the control range (spring range of the actuator) to provide a proper sequencing control of two or more controlled devices.

SENSORS

A sensor responds to a change in the controlled variable. The response, which is a change in some physical or electrical property of the primary sensing element, is available for translation or amplification by mechanical or electrical signal. This signal is sent to the controller.

Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications* and manufacturer's catalogs and tutorials include information on specific applications. In selecting a sensor for a specific application, consider the following:

- **Operating range of controlled variable.** The sensor must be capable of providing an adequate change in its output signal over the expected input range.
- **Compatibility of controller input.** Electronic and digital controllers accept various ranges and types of electronic signals. The sensor's signal must be compatible with the controller. If the controller's input requirements are unknown, it may be possible to use a transducer to convert the sensor signal to industry standard signal, such as 4 to 20 mA or 0 to 10 V (dc).
- **Accuracy and repeatability.** For some control applications, the controlled variable must be maintained within a narrow band around a desired set point. Both the accuracy and sensitivity of the sensor selected must reflect this requirement. However, even an accurate sensor cannot maintain the set point if (1) the controller is unable to resolve the input signal, (2) the controlled device cannot be positioned accurately, (3) the controlled device exhibits excessive hysteresis, or (4) disturbances drive its system faster than the controls can regulate it.
- **Sensor response time.** Associated with a sensor/transducer arrangement is a response curve, which describes the response of the sensor output to change in the controlled variable. If the time constant of the process being controlled is short and stable and accurate control is important, then the sensor selected must have a fast response time.
- **Control agent properties and characteristics.** The control agent is the medium to which the sensor is exposed, or with which it comes in contact, for measuring a controlled variable such as

temperature or pressure. If the agent corrodes the sensor or otherwise degrades its performance, a different sensor should be selected, or the sensor must be isolated or protected from direct contact with the control agent.

- **Ambient environment characteristics.** Even when the sensor's components are isolated from direct contact with the control agent, the ambient environment must be considered. The temperature and humidity range of the ambient environment must not reduce the sensor's accuracy. Likewise, the presence of certain gases, chemicals, and electromagnetic interference (EMI) can cause component degradation. In such cases, a special sensor or transducer housing can be used to protect the element, ensuring a true indication of the controlled variable.

Temperature Sensors

Temperature-sensing elements generally detect changes in either (1) relative dimension (caused by differences in thermal expansion), (2) the state of a vapor or liquid, or (3) some electrical property. Within each category, there are a variety of sensing elements to measure room, duct, water, and surface temperatures. Temperature-sensing technologies commonly used in HVAC applications are as follows:

- A **bimetal element** is composed of two thin strips of dissimilar metals fused together. Because the two metals have different coefficients of thermal expansion, the element bends and changes position as the temperature varies. Depending on the space available and the movement required, it may be straight, U-shaped, or wound into a spiral. This element is commonly used in room, insertion, and immersion thermostats.
- A **rod-and-tube element** consists of a high-expansion metal tube containing a low-expansion rod. One end of the rod is attached to the rear of the tube. The tube changes length with changes in temperature, causing the free end of the rod to move. This element is commonly used in certain insertion and immersion thermostats.
- A **sealed bellows element** is either vapor-, gas-, or liquid-filled. Temperature changes vary the pressure and volume of the gas or liquid, resulting in a change in force or a movement.
- A **remote bulb element** is a bulb or capsule connected to a sealed bellows or diaphragm by a capillary tube; the entire system is filled with vapor, gas, or liquid. Temperature changes at the bulb cause volume or pressure changes that are conveyed to the bellows or diaphragm through the capillary tube. This element is useful where the temperature-measuring point is remote from the desired thermostat location.
- A **thermistor** is a semiconductor that changes electrical resistance with temperature. It has a negative temperature coefficient (i.e., resistance decreases as temperature increases). Its characteristic curve of temperature versus resistance is nonlinear over a wide range. Several techniques are used to convert its response to a linear change over a particular temperature range. With digital control, one technique is to store a computer look-up table that maps the temperature corresponding to the measured resistance. The table breaks the curve into small segments, and each segment is assumed to be linear over its range. Thermistors are used because of their relatively low cost and the large change in resistance possible for a small change in temperature.
- A **resistance temperature device (RTD)** also changes resistance with temperature. Most metallic materials increase in resistance with increasing temperature; over limited ranges, this variation is linear for certain metals (e.g., platinum, copper, tungsten, nickel/iron alloys). Platinum, for example, is linear within ±0.3% from 0 to 300°F. The RTD sensing element is available in several forms for surface or immersion mounting. Flat grid windings are used for measurements of surface temperatures. For direct measurement of fluid temperatures, the windings are encased in a stainless steel bulb to protect them from corrosion.

Humidity Sensors

Humidity sensors, or **hygrometers**, measure relative humidity, dew point, or absolute humidity of ambient or moving air. Two types that detect relative humidity are mechanical hygrometers and electronic hygrometers.

A **mechanical hygrometer** operates on the principle that a hygroscopic material, usually a moisture-sensitive nylon or bulk polymer material, retains moisture and expands when exposed to water vapor. The change in size or form is detected by a mechanical linkage and converted to a pneumatic or electronic signal. Mechanical sensors using hair, wood, paper, or cotton are not widely used anymore because they are less accurate.

Electronic hygrometers can use either resistance or capacitance sensing elements. The resistance element is a conductive grid coated with a hygroscopic (water-absorbent) substance. The grid's conductivity varies with the water retained; thus, resistance varies with relative humidity. The conductive element is arranged in an ac-excited Wheatstone bridge and responds rapidly to humidity changes.

The capacitance element is a stretched membrane of nonconductive film, coated on both sides with metal electrodes and mounted in a perforated plastic capsule. The response of the sensor's capacity to rising relative humidity is nonlinear. The signal is linearized and temperature is compensated in the amplifier circuit to provide an output signal as relative humidity changes from 0 to 100%.

The **chilled-mirror humidity sensor** determines dew point rather than relative humidity. Air flows across a small mirror in the sensor. A thermoelectric cooler lowers the surface temperature of the mirror until it reaches the dew point of the air. Condensation on the surface reduces the amount of light reflected from the mirror compared to a reference light level.

Dispersive infrared (DIR) technology can be used to sense absolute humidity or dew point. It is similar to technology used to sense carbon dioxide or other gases. Infrared water vapor sensors are optical sensors that detect the amount of water vapor in air based on the infrared light absorption characteristics of water molecules. Light absorption is proportional to the number of molecules present. An **infrared hygrometer** typically provides a value of absolute humidity or dew point, and can operate in diffusion or flow-through sample mode. This type of humidity sensor is unique in that the sensing element (a light detector and an infrared filter) is behind a transparent window and is never exposed directly to the sample environment. As a result, this sensor has excellent long-term stability and life and fast response time, is not subject to saturation, and operates equally well in very high or low humidity. Previously used solely for high-end applications, infrared hygrometers are now commonly used in HVAC applications because they cost about the same as mid-range-accuracy (1 to 3%) humidity sensors.

Pressure Transmitters and Transducers

A pneumatic pressure transmitter converts a change in absolute, gage, or differential pressure to a mechanical motion using a bellows, diaphragm, or Bourdon tube mechanism. When corrected through appropriate links, this mechanical motion produces a change in air pressure to a controller. In some instances, sensing and control functions are combined in a single component, a pressure controller.

An electronic pressure transducer may use mechanical actuation of a diaphragm or Bourdon tube to operate a potentiometer or differential transformer. Another type uses a strain gage bonded to a diaphragm. The strain gage detects displacement resulting from the force applied to the diaphragm. Capacitance transducers are most often used for measurements below 1 in. of water because of their high sensitivity and repeatability. Electronic circuits provide temperature compensation and amplification to produce a standard output signal.

Flow Rate Sensors

Orifice plate, pitot-static tube, venturi, turbine, magnetic flow, thermal dispersion, vortex shedding, and Doppler effect meters are some of the technologies used to sense fluid flow. In general, pressure differential devices (orifice plates, venturi, and pitot tubes) are less expensive and simpler to use, but have limited range; thus, their accuracy depends on how they are applied and where in a system they are located.

More sophisticated flow devices, such as turbine, magnetic, and vortex shedding meters, usually have better range and are more accurate over a wide range. If an existing piping system is being considered for retrofit with a flow device, the expense of shutting down the system and cutting into a pipe must be considered. In this case, a noninvasive meter, such as a Doppler effect meter, can be cost-effective.

For air velocity metering, pitot-static tubes provide a naturally larger signal change at high velocities, with limitations on their application below 500 to 600 fpm. Vortex shedding for airflow applications has similar low velocity limitations. Thermal dispersion sensors provide a naturally larger signal change at lower velocities without appreciable losses through velocities common in most ventilation systems, which makes them more suitable for applications below 1000 fpm.

Indoor Air Quality Sensors

Indoor air quality control can be divided into two categories: ventilation control and contamination protection. In spaces with dense populations and intermittent or highly variable occupancy, ventilation can be more efficiently applied by detecting changes in population or ventilation requirements (**demand-controlled ventilation**). This involves using time schedules and population counters and measuring the indoor/outdoor differential levels of carbon dioxide (CO_2) or other contaminants in a space; the amount of outdoor air introduced into the occupied space is then controlled. Demand control helps maintain proper ventilation rates at all levels of occupancy. Control set-point levels for carbon dioxide are determined by the specific relationships between differential CO_2, rate of CO_2 production by occupants, the variable airflow rate required by the changing population, and a fixed amount of ventilation required to dilute building-generated contaminants unrelated to CO_2 production. ASHRAE *Standard* 62.1 and its user's manual (ASHRAE 2007) provide further information on ventilation for acceptable indoor air quality.

Contamination protection sensors monitor levels of hazardous or toxic substances and issue warning signals and/or initiate corrective actions through the building automation system (BAS). Sensors are available for many different gases. The carbon monoxide (CO) sensor is one of the most common, and is often used in buildings wherever combustion occurs (e.g., parking garages). Refrigerant-specific sensors are used to measure, alarm, and initiate ventilation purging in enclosed spaces that house refrigeration equipment, to prevent occupant suffocation upon a refrigeration leak (see ASHRAE *Standard* 15 for more information). The application of these sensors determines the type selected, the substances monitored, and the action taken in an alarm condition.

Lighting Level Sensors

Analog lighting level transmitters packaged in various configurations allow control of ambient lighting levels using building automation strategies for energy conservation. Examples include ceiling-mounted indoor light sensors used to measure room lighting levels; outdoor ambient lighting sensors used to control parking, general exterior, security, and sign lighting; and interior skylight sensors used to monitor and control light levels in skylight wells and other atrium spaces.

Power Sensing and Transmission

Passive electronic devices that sense the magnetic field around a conductor carrying current allow low-cost instrumentation of power circuits. A wire in the sensor forms an inductive coupling that powers the internal function and senses the level of the power signal. These devices can provide an analog output signal to monitor current flow or operate a switch at a user-set level to turn on an alarm or other device.

CONTROLLERS

A controller compares the sensor's signal with a desired set point and regulates an output signal to a controlled device. Digital controllers perform the control function using a microprocessor and control algorithm. The sensor and controller can be combined in a single instrument, such as a room thermostat, or they may be two separate devices.

Digital Controllers

Digital controls use microprocessors to execute software programs that are customized for use in commercial buildings. Controllers use sensors to measure values such as temperature and humidity, perform control routines in software programs, and perform control using output signals to actuators such as valves and electric or pneumatic actuators connected to dampers. The operator may enter parameters such as set points, proportional or integral gains, minimum on and off times, or high and low limits, but the control algorithms make the control decisions. The computer scans input devices, executes control algorithms, and then positions the output device(s), in a stepwise scheme. The controller calculates proper control signals digitally rather than using an analog circuit or mechanical change, as in electric/electronic and pneumatic controllers. Use of digital controls in building automation is referred to as direct digital control (DDC).

Digital controls can be used as stand-alones or can be integrated into building management systems though network communications. Simple controls may have a single control loop that can perform a single control function (e.g., temperature control of a unit ventilator), or larger versions can control a larger number of loops.

Advantages of digital controls include the following:

- Sequences or equipment can be modified by changing software, which reduces the cost and diversity of hardware necessary to achieve control.
- Features such as demand setback, reset, data logging, diagnostics, and time-clock integration can be added to the controller with small incremental cost.
- Precise, accurate control can be implemented, limited by the resolution of sensor and analog-to-digital (A/D) and digital-to-analog (D/A) conversion processes. PID and other control algorithms can be implemented mathematically and can adjust performance based on multiple sequences or inputs.
- Controls can communicate with each other using open or proprietary networking (e.g., Ethernet or Internet) standards.

Digital controls can operate at the system level, which includes applications that span multiple HVAC applications or single-zone controllers.

A single control that is fixed in functionality with flexibility to change set points and small configurations is called an **application-specific controller**. Many manufacturers include application-specific controls with their HVAC equipment, such as air-handling units and chillers.

Firmware and Software. Preprogrammed control routines, known as firmware, are sometimes stored in permanent memory such as programmable read-only memory (PROM) or electrically programmable read-only memory (EPROM), and the application or set points are stored in changeable memory such as electrically erasable programmable read-only memory (EEPROM). The operator can modify parameters such as set points, limits, and minimum *off* times within the control routines, but the primary program logic cannot be changed without replacing the memory chips.

User-programmable controllers allow the algorithms to be changed by the user. The programming language provided with the controller can vary from a derivation of a standard language to custom language developed by the controller's manufacturer, to graphically based programming. Preprogrammed routines for proportional, proportional plus integral, Boolean logic, timers, etc., are typically included in the language. Standard energy management routines may also be preprogrammed and may interact with other control loops where appropriate.

Digital controllers can have both preprogrammed firmware and user-programmed routines. These routines can automatically modify the firmware's parameters according to user-defined conditions to accomplish the control sequence designed by the control engineer.

Operator Interface. Some digital controllers (e.g., a programmable room thermostat) are designed for dedicated purposes and are adjustable only through manual switches and potentiometers mounted on the controller. This type of controller cannot be networked with other controllers. A **direct digital controller** can have manually adjustable features, but it is more typically adjusted through a built-in LED or LCD display, a hand-held device, or a terminal or computer. The direct digital controller's digital communication allows remote connection to other controllers and to higher-level computing devices and host operating stations.

A **terminal** allows the user to communicate with the controller and, where applicable, to modify the program in the controller. Terminals can range from hand-held units with an LCD display and several buttons to a full-sized console with a video monitor and keyboard. The terminal can be limited in function to allow only display of sensor and parameter values, or powerful enough to allow changing or reprogramming the control strategies. In some instances, a terminal can communicate remotely with one or more controllers, thus allowing central displays, alarms, and commands. Usually, hand-held terminals are used by technicians for troubleshooting, and full-sized, fully functional terminals are used at a fixed location to monitor the entire digital control system. Standard Internet browsers can be used to access system information.

Electric/Electronic Controllers

For **two-position control**, the controller output may be a simple electrical contact that starts a fan or pump, or one that actuates a spring-return valve or damper actuator. **Single-pole, double-throw (SPDT)** switching circuits control a three-wire unidirectional motor actuator. SPDT circuits are also used for heating and cooling applications. Both single-pole, single-throw (SPST) and SPDT circuits can be modified for timed two-position action.

Output for **floating control** is a SPDT switching circuit with a neutral zone where neither contact is made. This control is used with reversible motors; it has a slow response and a wide throttling range.

Pulse modulation control is an improvement over floating control. It provides closer control by varying the duration of the contact closure. As the actual condition moves closer to the set point, the pulse duration shortens for closer control. As the actual condition moves farther from the set point, the pulse duration lengthens.

Proportional control gives continuous or incremental changes in output signal to position an electrical actuator or controlled device.

Pneumatic Receiver-Controllers

Pneumatic receiver-controllers are normally combined with pneumatic elements that use a mechanical force or position reaction to the sensed variable to obtain a variable-output air pressure. Control is usually proportional, but other modes (e.g., proportional-plus-integral) can be used. These controllers are generally classified as nonrelay or relay, and as direct-acting or reverse-acting.

The nonrelay pneumatic controller uses low-volume output. A relay pneumatic controller actuates a relay device that amplifies the air volume available for control. The relay provides quicker response to a variable change.

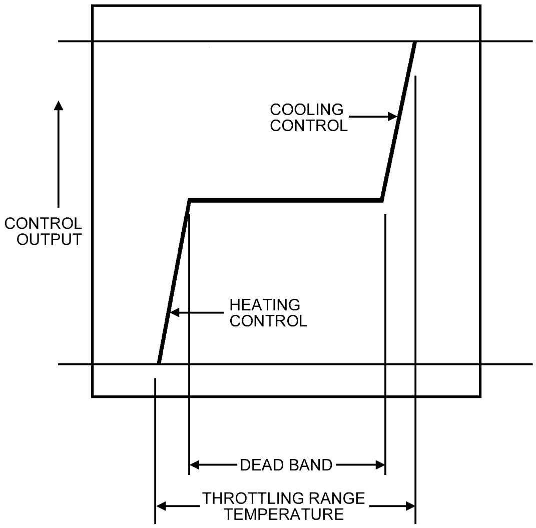


Fig. 16 Dead-Band Thermostat

Direct-acting controllers increase the output signal as the controlled variable increases. Reverse-acting controllers increase the output signal as the controlled variable decreases. A reverse-acting thermostat increases output pressure when the temperature drops.

Thermostats

Thermostats combine sensing and control functions in a single device. Microprocessor-based thermostats have many of the following features.

- An **occupied/unoccupied** or **dual-temperature room thermostat** controls at an offset temperature at night. It may be indexed (changed from occupied to unoccupied) individually or in a group by a manual switch or time switch from a remote point. Some electric units have an individual clock and switch built into the thermostat.
- A **pneumatic day/night thermostat** uses a two-pressure air supply system (often 13 and 17 psig, or 15 and 20 psig). Changing pressure at a central point from one value to the other actuates switching devices in the thermostat that index it from occupied to unoccupied or vice versa.
- A **heating/cooling** or **summer/winter thermostat** can have its action reversed and its set point changed by indexing. It is used to actuate controlled devices, such as valves or dampers, that regulate a heating source at one time and a cooling source at another.
- A **multistage thermostat** operates two or more successive steps in sequence.
- A **submaster thermostat** has its set point raised or lowered over a predetermined range in accordance with variations in output from a master controller. The master controller can be a thermostat, manual switch, pressure controller, or similar device.
- A **dead-band thermostat** has a wide differential over which the thermostat remains neutral, requiring neither heating nor cooling. This differential may be adjustable up to 10°F. The thermostat then controls to maximum or minimum output over a small differential at the end of each dead band (Figure 16).

AUXILIARY CONTROL DEVICES

Auxiliary control devices for electric systems include

- **Transformers** to provide current at the required voltage.

- **Occupancy sensors** to automatically adjust controlled variables (e.g., lighting, ventilation rate, and temperature) based on occupancy.
- **Signal transducers** to change one standard signal into another. The popularity of digital control and other electric-based control systems has generated a variety of transducers. Variables usually transformed include voltage [0 to 10, 0 to 5, 2 to 10 V (dc)], current (4 to 20 mA), resistance (0 to 135 Ω), pressure (3 to 15, 0 to 20 psig), phase cut voltage [0 to 20 V (dc)], pulse-width modulation, and time duration pulse. Signal transducers allow use of an existing control device in a retrofit application.
- **Electric relays** to control electric heaters or to start and stop burners, compressors, fans, pumps, or other apparatus for which the electrical load is too large to be handled directly by the controller. Other uses include time-delay and circuit-interlocking safety applications. Form letters are part of an ANSI standard that defines the arrangement of contacts for relays and switches. The three most common types in HVAC are forms A, B, and C. Form A relays are single-pole, single-throw, normally open (SPST-NO). Form B relays are single-pole, single-throw, normally closed (SPST-NC). Form C relays are single-pole, double-throw (SPDT) and can be either normally open or normally closed, so control panels can be built using all form C (SPDT) relays. In small sizes, the added cost of the second contact is insignificant. As current ratings go up, forms A and B become more cost-effective.
- **Control relay sockets** are used with control relays to terminate wires from the device being switched or controlled. They may have either blade- or pin-type terminals.
- **Relays** are available prewired in a field-mounted housing using a 0.5 in. knockout in a panel or motor starter. The coil requires a low current to operate the relay, which can control either ac or dc power loads. The device typically has an LED indicator and may have an optional hand-off-auto switch.
- **Time-delay relays**, similar to control relays, include an adjustable time delay that is set using dipswitches and an external knob. The device is either a delay-on-make (*on* delay) or delay-on-break (*off* delay). The time delay is either in seconds to minutes or minutes to hours.
- **Power relays** handle high-power switching of electrical loads in motor control centers and lighting control applications. They may be of open-frame construction or may be encased by a clear polycarbonate cover. They may be either single- or multiple-pole devices that are field- or panel-mounted.
- **Solid-state relays** are photo-isolated and optically isolated relays used to switch voltages up to 600 V with high amperage loads using a form-A, normally open contact. They have a high surge dielectric strength, and reverse voltage protection. They operate using an input voltage of 4 to 32 V dc. Operation of this device is easily affected by high temperatures and induced currents.
- **Potentiometers** are used for manual positioning of proportional control devices, for remote set-point adjustment of electronic controllers, and for feedback.
- **Manual switches**, either two-position or multiple-position with single or multiple poles, are used to switch equipment from one state to another.
- **Auxiliary switches** on valve and damper actuators are used to select a sequence of operation.
- **Smoke detectors** provide early detection of both smoke and other combustion products in air moving through HVAC ducts. Sampling tubes, selected based on duct size, test air moving in the duct. Based on the application, either a photoelectric or ionization head is installed in the device. The device typically has two alarm contacts, used to shut down the associated equipment and provide remote indication, and a trouble contact, which monitors incoming power and removal of the detector head. Where a fire alarm system is installed, the smoke detectors must be listed for use with the fire alarm system. Addressable fire alarm systems may use a programmable relay for fan shutdown rather than a hard-wired connection to the detector.
- **Transient voltage surge suppressors (TVSSs)**, formerly called **lightning arrestors**, protect communication lines and critical power lines between buildings or at building entrance vaults against high-voltage transients caused by variable-frequency drives, motors, transmitters, and lightning. To be effective, they must be grounded to a grounding rod in compliance with the National Electric Code and the manufacturer's recommendations.
- **Analog time switches** are set manually to control an electrical load. They are spring-wound and have either normally open or normally closed contacts. Timing is either in minutes or hours and may have an override hold feature to keep the load on or off continuously.
- **Digital time switches** are set manually to control an electrical load and have either normally open or normally closed contacts. The timing function is either in minutes or hours, and may have an override hold feature to keep the load on or off continuously, a flash option, or a beeper option to notify the operator that the load will be turning off shortly.
- **Time clocks** (mechanical or electronic) turn electrical loads on and off, based on a 24 h/7 day or 24 h/365 day schedule.
- **Regulated dc power supply** devices convert ac voltage into a regulated dc voltage between 12 and 24 V dc. They may be used to power temperature and humidity transmitters.
- **Fuses** are safety devices with a specific amp rating, used with power supplies, circuit boards, control transformers, and transducers. They may be rated for either high or low inrush currents, and are available in slow-blow or fast-acting models.
- **Strobes** are lights that use a high-intensity xenon flash tube to generate a high-intensity light that is visible in all directions. If this device is used in a safety application such as refrigeration monitoring, it must comply with UL *Standard* 1971.
- **Horns** provide an audible tone with a specified loudness rated in decibels (dB), and are mounted in a panel or junction box. Its tone may be continuous, warbled, short beeps, or long beeps. The tone should be at least 10 dB above the ambient noise level in the area that the device is mounted. The operating voltage may be either dc or ac.

Auxiliary control devices for pneumatic systems include

- **Air compressors** and accessories, including driers, filters, and pressure regulators, provide a source of clean, dry air at the required pressure.
- **Electropneumatic relays** are electrically actuated air valves that operate pneumatic equipment according to variations in electrical input to the relay.
- **Pneumatic-electric switches**, driven by pressure from a controller, allow a controller actuating a proportional device to also actuate one or more two-position devices.
- **Pneumatic transducers**, which reverse the action of a proportional controller, select the higher or lower of two or more pressures, average two or more pressures, respond to the difference between two pressures, add or subtract pressures, and amplify or retard pressure changes.
- **Positive-positioning relays** ensure accurate positioning of a valve or damper actuator in response to changes in pressure from a controller.
- **Switching relays** are pneumatically operated air valves used to divert air from one circuit to another or to open and close air circuits.
- Manually operated **pneumatic switches** divert air from one circuit to another or open and close air circuits. They can be two-position or multiple-position.
- **Gradual switches** are proportional devices used to manually vary air pressure in a circuit.

Auxiliary control devices common to both electric and pneumatic systems include the following:

- **Step controllers** operate several switches in sequence using a proportional electric or pneumatic actuator. They are commonly used to control several steps of refrigeration capacity. They may be arranged to prevent simultaneous starting of compressors and to alternate the sequence to equalize wear. These controllers may also be used for sequenced operation of electric heating elements and other equipment.
- **Power controllers** control electric power input to resistance heating elements. They are available with various ratings for single- or three-phase heater loads and are usually arranged to regulate power input to the heater in response to the demands of the proportional electronic or pneumatic controllers. A **silicon controlled rectifier (SCR)** is the most common form of power controller used for electric heat. Solid-state controllers may also be used in two-position control modes because they do not use contacts, which can arc when power is applied or removed.
- **Clocks** or **timers** turn apparatus on and off at predetermined times, switch control systems from day to night operation, and regulate other time-sequence functions.
- **High-temperature limits** are safety devices, typically set at 125 to 150°F, that shut down equipment when the temperature exceeds its set point. A manual reset reactivates the device once the condition has cleared. These devices are typically used when airflow is less than 2000 cfm. **Low-temperature limits** typically have a 20 ft long vapor-charged sensing element, set at 35°F, that shuts down equipment when the temperature in a 12 or 18 in. section falls below its set point. The limit may be manually or automatically reset. The device must be mounted parallel to the tubes with capillary mounting clips for proper measurement. The device may be either SPST or double-pole, double-throw (DPDT). A typical use is to protect chilled-water coils from freezing.
- **Transducers**, which consist of combinations of electric and pneumatic control devices, convert electric signals to pneumatic output or vice versa. Transducers may convert proportional input to either proportional or two-position output.

  The **electronic-to-pneumatic transducer (EPT)** is used in many applications. It converts a proportional electronic output signal into a proportional pneumatic signal (Figure 17) and can be used to combine electronic and pneumatic control components to form a control loop (Figure 18). Electronic components are used for sensing and signal conditioning, whereas pneumatic components are used for actuation. The electronic controller can be either analog or digital.

  The EPT presents a special option for retrofit applications. An existing HVAC system with pneumatic controls can be retrofitted with electronic sensors and controllers while retaining the existing pneumatic actuators (Figure 19).

- **Thermostat guards** are plastic or metal covers that protect switches, thermostat controllers, and sensors from damage, tampering, and unauthorized adjustment.
- **Enclosures** may be used indoors or outdoors to protect equipment and people. Enclosures are rated by the National Electrical Manufacturers Association (NEMA *Standard* 250) and Electrical and Electronic Manufacturer Association of Canada (EEMAC).
- **Pilot lights** are replaceable incandescent or light-emitting diode (LED) lights that indicate modes of operation of mechanical and electrical equipment. They are panel-mounted, and may be round or flat, of various colors, and powered using either ac or dc power. They are typically installed in an enclosure rated for the application under National Electrical Manufacturers Association (NEMA) *Standard* 250.
- **Three-** and **five-valve manifolds** protect water differential pressure sensors from overpressurization during installation, start-up, shutdown, system testing, and maintenance. Three-valve manifolds are comprised of two isolation valves and a bypass valve. A five-valve manifold includes two additional valves to allow online calibration. Depending on the application, snubbers may be required, as well.

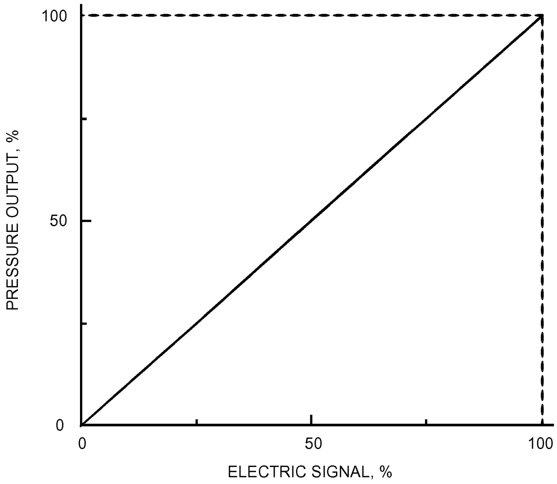


Fig. 17 Response of Electronic-to-Pneumatic Transducer (EPT)

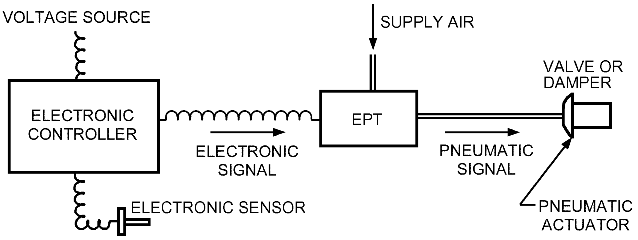


Fig. 18 Electronic and Pneumatic Control Components Combined with Electronic-to-Pneumatic Transducer (EPT)

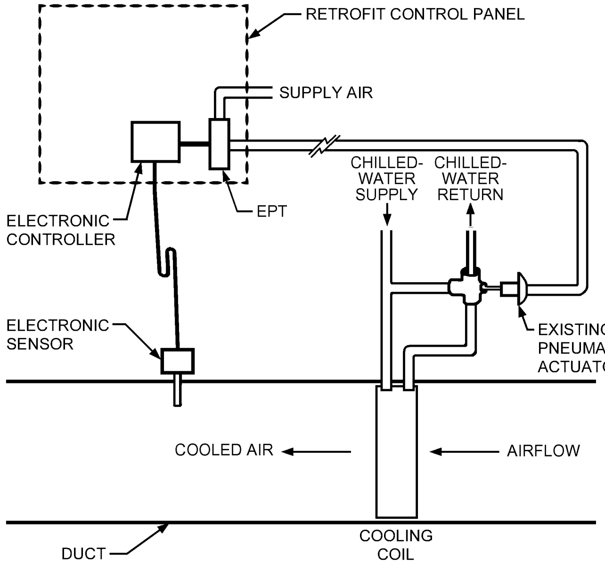


Fig. 19 Retrofit of Existing Pneumatic Control with Electronic Sensors and Controllers

- **Snubbers**, made of brass or stainless steel, stop shocks and pulsations caused by fluid hammering and system surges. Two types of pressure snubbers are used in HVAC applications: porous and piston. A porous snubber has no moving parts and uses a porous material to stop device damage. A piston snubber uses a moving piston inside a tube that moves up and down to stop device damage and push away any sediment or scale that may clog the system's monitoring devices. Depending on the application, the type of piston to be used may need to be specified.
- **Steam pigtail siphons** protect pressure transmitters from the high temperature of steam. They are typically made from steel or stainless steel of a specific length with a loop. The temperature of the medium being monitored determines the length and material. Most pressure devices have an operating temperature range of 0 to 200°F.

COMMUNICATION NETWORKS FOR BUILDING AUTOMATION SYSTEMS

A **building automation system (BAS)** is a centralized control and/or monitoring system for many or all building systems (e.g., HVAC, electrical, life safety, security). A BAS may link information from control systems actuated by different technologies.

One important characteristic of direct digital control (DDC) is the ability to share information. Information is transferred between (1) controllers to coordinate their action, (2) controllers and building operator interfaces to monitor and command systems, and (3) controllers and other computers for off-line calculation. This information is typically shared over communication networks. DDC systems nearly always involve at least one network; often, two or more networks are interconnected to form an **internetwork**.

COMMUNICATION PROTOCOLS

A communication protocol is a set of rules that define communication behavior of each component in a communication network. These rules define the content and format of messages to be exchanged, error detection and recovery, addressing, when a device may transmit a message, electrical signaling characteristics, and details of the communication medium such as wire type and pin connections. Protocols are often defined by dividing the complex problem into several simpler problems that, when solved in a particular order, meet the overall communication needs. Component parts of the overall solution are called **layers**. A protocol may provide the functionality of a particular layer or group of layers, or address the entire communication process.

Layering is very important because it allows portions of the technology to be used by a wide variety of applications, and thus lowers the cost because of economies of scale. For example, one of the most widely used computer communication standards is the Institute of Electrical and Electronics Engineers (IEEE) *Standard* 802.3 (Ethernet). Ethernet is a general-purpose mechanism for exchanging information across a local area network (LAN). Ethernet networks are used for many applications, including e-mail, file transfer, Web browsing, and building control systems. However, two devices on the same Ethernet may not be able to communicate at all because Ethernet does not define the content of messages to be exchanged.

There is great interest in open protocols for building automation systems to facilitate communication among devices from different suppliers. Although there is no commonly accepted definition of "openness," IEEE *Standard* 802.3 defines three classes of protocols:

- **Standard protocol.** Published and controlled by a standards body.
- **Public protocol.** Published but controlled by a private organization.

7 Application Layer	Window between applications and network.
6 Presentation Layer	Coordinates representation of information between different applications.
5 Session Layer	Synchronizes and structures exchange of data messages between specific users.
4 Transport Layer	Converts data messages into packets for transmission, and converts received packets into messages. Responsible for data message error recognition and recovery, and ensures reliable delivery of messages.
3 Network Layer	Addressing and routing packets independent of media and topology.
2 Data Link Layer	Responsible for point-to-point reliability. Media access. Representation of bits and bytes as physical signals. Organizes bits into data packets.
1 Physical Layer	Electrical characteristics of devices and conductors.

Fig. 20 OSI Reference Model

- **Private protocol.** Unpublished; use and specification controlled by a private organization. Examples include the proprietary communications used by many building automation devices.

Multivendor communication is possible with any of these three classes, but the challenges vary. Specifying a standard or widely used public protocol can improve the chances for a competitive bidding process and provide economic options for future expansions. However, specifying a common protocol does not ensure that the requirement for interoperability is met. It is also necessary to specify the desired interaction between devices.

OSI NETWORK MODEL

ISO *Standard* 7498-1 presents a seven-layer model of information exchange called the Open Systems Interconnection (OSI) Reference Model (Figure 20). Most descriptions of computer networks, especially open networks, are based on this reference model. The layers can be thought of as steps in the translation of a message from something with meaning at the application layer, to something measurable at the physical layer, and back to meaningful information at the application layer.

The full seven-layer model does not apply to every network, but it is still used to describe the aspects that fit. When describing DDC networks that use the same technology throughout the system, the seven-layer model is relatively unimportant. For systems that use various technologies at different points in the network, the model helps to describe where and how the pieces are bound together.

NETWORK STRUCTURE

Often, a single DDC system applies different network technologies at different points in the system. For example, a relatively low-speed, inexpensive network with relatively primitive functions may link a group of room controllers to a supervisory controller. A faster, more sophisticated network may link the supervisory controller to its peers and to one or more operator workstations. Figure 21 illustrates this sort of high-speed hierarchical network. Structures like it have been popular in DDC for years. Frequently, the network hierarchy corresponds roughly to a hierarchy related to the control function of the devices, but variations continue to emerge. The opposite extreme is a completely flat network architecture. A flat architecture links all devices through the same network. A flat architecture is more viable in small systems than in large ones, because economic constraints typically dictate that low-cost (and therefore low-speed)

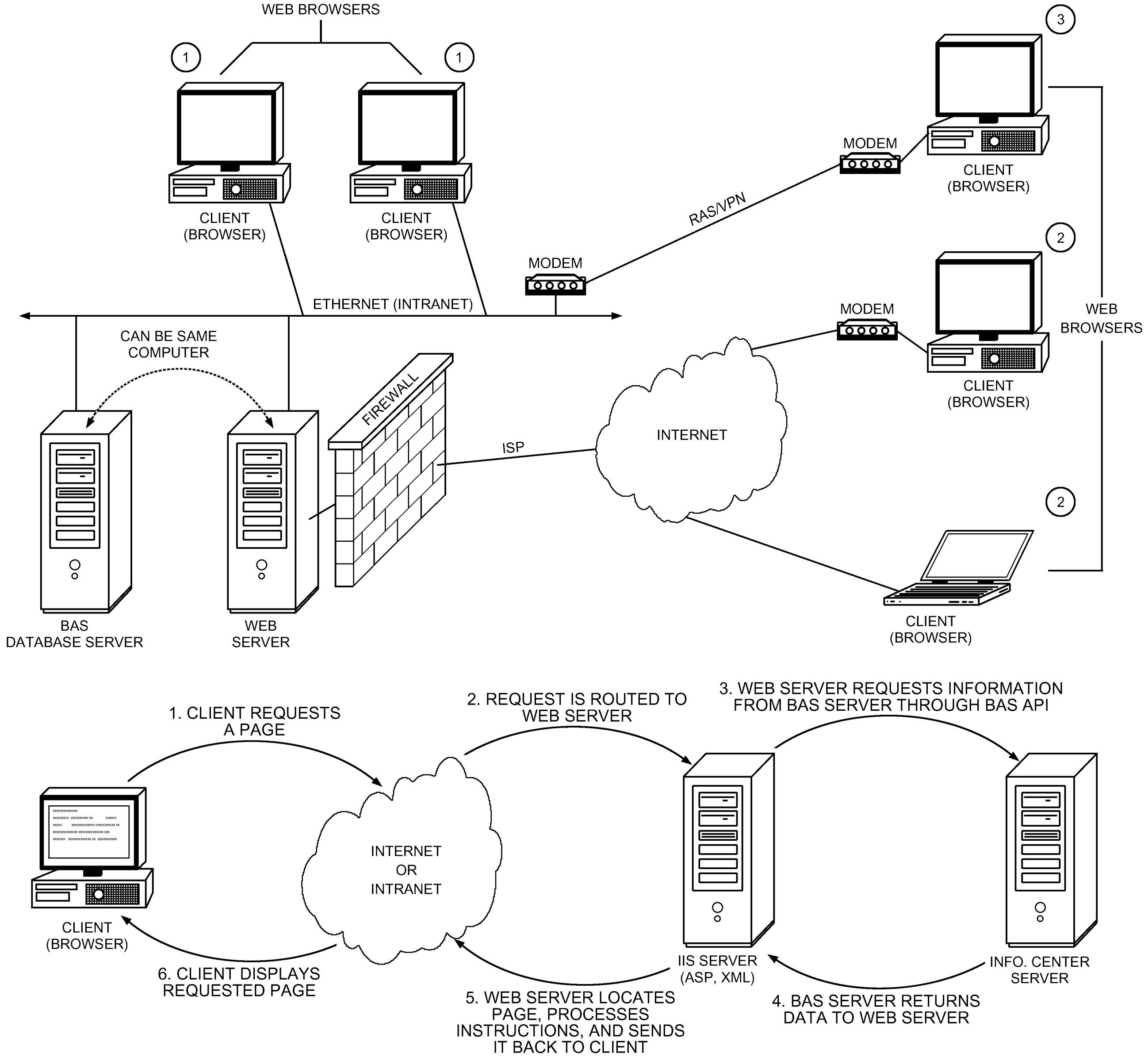


Fig. 21 Hierarchical Network

networks be used to connect field-level controllers. Because of their performance limitations, these networks do not scale well to large numbers of devices. As the cost of electronics for communication drops, the flatter networks become more feasible.

Network structure can affect

- Opportunities for expansion of a BAS.
- Reliability and failure modes. It may be appropriate to separate sections of a network to isolate failures.
- How devices load the information-carrying capacity of the network. It can isolate one busy branch from the rest of the system, or isolate branches from the high-speed backbone.
- How and where information is displayed to operating personnel; Web servers accessible through the Internet make BAS information available to anyone, anywhere, who has a standard Web browser and access rights to view the server pages.
- System cost, because it determines the mix of low- and high-speed devices.
- System data security and access control.

The relative merits of one structure versus another depend on the communication functions required, hardware and software available for the task, and cost. For a given job, there is probably more than one suitable structure. Product capabilities change quickly. Engineers who choose to specify network structure must be aware of new technologies to take advantage of the most cost-effective solutions.

Connections Between BAS Networks and Other Computer Networks

Some BAS networks use other networks to connect segments of the BAS. This occurs

- Within a building, using the information technology network
- Between buildings, using an intranet or the Internet
- Between buildings, using telephone lines

In each case, the link between BAS segments must be considered part of the BAS network when evaluating function, security, and performance. The link also raises new issues. The connecting segment is likely to be outside the control of the owner of the BAS, which could affect availability of service. Traffic and bandwidth issues may have to be addressed outside the facilities department.

Using a dial-up connection to interact with a remote building or to serve a remote operator requires consideration of which segment may dial the other, what circumstances trigger the call, and security implications. Handling interbuilding communication through intranet or Internet connections, with the operator interface provided by a Web browser communicating with a Web server, has largely replaced dial-up connections.

Transmission Media

The transmission medium is the foundation of the network. It is usually, but not always, cable. The cable may be plenum-rated or non-plenum-rated, depending on the installation application. Where physical cable connection is not possible or practical, devices may transfer information using wireless technologies, such as radio waves or infrared light. However, this section covers only physical cabling media. ANSI/TIA/EIA *Standard* 568-B.1 provides cabling specifications for commercial buildings.

Cable length. The maximum cable length varies with cable type, transmission speed, and the protocol.

100 Ω Balanced Twisted-Pair Communications Outlet/ Connector. Each four-pair cable terminates on an eight-position modular jack, and all unshielded twisted-pair (UTP) and screened twisted-pair (ScTP) telecommunications outlets must meet the requirements of IEC *Standard* 60603-7, as well as ANSI/TIA/EIA *Standard* 568-B.2 and the terminal marking and mounting requirements of ANSI/TIA/EIA *Standard* 570-B.

Twisted-Pair Copper Cable. A twisted-pair cable consists of multiple twisted pairs (typically 24 AWG) of wire covered by an overall sheath or jacket. Varying the number of twists for each pair relative to the other pairs in the cable can greatly reduce crosstalk (interference between signals on different pairs).

Screened twisted-pair (ScTP) cable is similar in construction to UTP data cabling, except that ScTP has a foil shield between the conductors and outer jacket, as well as a drain wire used to minimize interference-related problems. ScTP cable is preferred over UTP cable in environments where high immunity and/or low emissions are critical. It also allows less crosstalk than UTP. However, ScTP requires more labor-intensive installation, and any break or improper grounding of the shield reduces its overall effectiveness.

Category 3 cable connects hardware and patch cords that are rated to a maximum frequency of 16 MHz. This cable is rated up to 16 megabits per second. This category is usually the lowest level of cable installed and is used mainly for voice and low-speed networks.

Category 5 cable connects hardware and patch cords that are rated to a maximum frequency of 100 MHz. The actual data transmission rate varies with the compression scheme used. Category 5 was defined in ANSI/TIA/EIA *Standard* 568-A, but is no longer recognized in the new ANSI/TIA/EIA *Standard* 568-B.1.

Category 5e cable connects hardware and patch cords that are rated to a maximum frequency of 100 MHz. The actual data transmission rate varies with the compression or encoding scheme used. Category 5e, the lowest category recommended for data installations, is defined by ANSI/TIA/EIA *Standards* 568-B.1 and B.2. This cable is rated up to 100 megabits per second.

Table 1 Comparison of Fiber Optic Technology

	Multimode Fiber	Single-Mode Fiber
Light source	LED	Laser
Cable designation (core/cladding diameter)	62.6/125	8.3/125
Transmission distance	660 ft	980 ft
Data rate	>10 gigabit/s and increasing	Even higher
Relative cost	Less per connection, more per data rate	More per connection, less per data rate

Category 6 cable connects hardware and patch cords that are rated to a maximum frequency of 250 MHz, though the actual data transmission rate varies with the compression scheme used. UTP or STP cable is currently the most common medium. This cable is rated up to 1 gigabit per second.

Category 6e cable connects hardware and patch cords that are rated to a maximum frequency of 250 MHz, though actual data transmission rate varies with the compression scheme used. With all Category 6 systems, an eight-position jack is mandatory in the work area.

Category 7 cable connects hardware and patch cords that are rated to a maximum frequency of 600 MHz, though actual data transmission rate varies with the compression scheme used. This category is still in development and uses a braided shield surrounding all four foil shielded pairs to reduce noise and interference. Depending on future technological developments, the current RJ-45 connector will not be used in Category 7.

Fiber-Optic Cable. Fiber-optic cable uses glass or plastic fibers to transfer data in the form of light pulses, which are typically generated by either a laser or an LED. Fiber-optic cable systems are classified as either single-mode fiber or multimode fiber systems. Table 1 compares their characteristics.

Light in a fiber-optic system loses less energy than electrical signals traveling through copper and has no capacitance. This translates into greater transmission distances and dramatically higher data transfer rates, which impose no limits on a BAS. Fiber optics also have exceptional noise immunity. However, the necessary conversions between light-based signaling and electricity-based computing make fiber optics more expensive per device, which sometimes offsets its advantages.

Structured Cabling. ANSI/TIA/EIA *Standard* 568, Commercial Building Telecommunications Cabling Standard, allows cable planning and installation to begin before the network engineering is finalized. It supports both voice and data. The standard was written for the telecommunications industry, but cabling is gaining recognition as building infrastructure, and the standard is being applied to BAS networks as well.

ANSI/TIA/EIA *Standard* 568-B specifies **star topology** (each device individually cabled to a hub) because connectivity is more robust and management is simpler than for busses and rings. If the wires in a leg are shorted, only that leg fails, making fault isolation easier; with a bus, all drops would fail.

The basic structure specified is a **backbone**, which typically runs from floor to floor within a building and possibly between buildings. **Horizontal cabling** runs between the distribution frames on each floor and the information outlets in the work areas.

Wireless Sensors and Controls. The rapid maturity of everyday wireless technologies, now widely used for mobile phones, Internet access, and even barcode replacement, has tremendously increased the ability to collect information from the physical world. Wireless technologies offer significant opportunities in sensors and controls for building operation, especially in reducing the cost of installing data acquisition and control devices. Installation costs typically represent 20 to 80% of the total cost of a sensor and control point in any HVAC system, so reducing or eliminating the cost of installation has a dramatic effect on the overall installed system cost. Low-cost wireless sensors and control systems also make it economical to use more sensors, thereby establishing highly energy-efficient building operations and demand responsiveness that enhance the electric grid reliability.

Wireless sensors and control networks consist of sensor and control devices that are connected to a network using radio-frequency (RF) or optical (infrared) signals. Devices can communicate bidirectionally (i.e., transmitting and receiving) or one way (transmitting only). Most RF products transmit in the industrial, scientific, or medical frequency bands, which are set aside by the Federal Communication Commission (FCC) for use without an FCC license. Wireless sensor networks have different requirements than computer networks and, thus, different network topologies, and separate communication protocols have evolved for them. The simplest is the **point-to-point topology**, in which two nodes communicate directly with each other. The **point-to-multipoint** or **star topology** is an extension of the point-to-point configuration in which many nodes communicate with a central receiving or gateway node. In either topology, sensor nodes might have pure transmitters, which provide one-way communication only, or transceivers, which enable two-way communication and verification of the receipt of messages. Gateways provide a means to convert and pass data between protocols (e.g., from a wireless sensor network protocol to the wired Ethernet protocol).

The communication range of the point-to-point and star topologies is limited by the maximum communication range between the sensor node (from which the measured data originates) and the receiver node. This range can be extended by using repeaters, which receive transmissions from sensor nodes and then retransmit them, usually at higher power than the original transmissions. In the **mesh network topology**, each sensor node includes a transceiver that can communicate directly with any other node within its communication range. These networks connect many devices to many other devices, thus forming a mesh of nodes in which signals are transmitted between distant points via multiple hops. This approach decreases the distance over which each node must communicate and reduces each node's power use substantially, making them more compatible with onboard power sources such as batteries (Capehardt 2005).

SPECIFYING BAS NETWORKS

Specifying a DDC system includes specifying a network. The many network technologies available deliver many performance levels at many different prices. Rational selection requires assessing the requirements (i.e., what information will pass between devices and at what rates). In some cases, new equipment must interface with existing devices, which may limit networking options.

Specification Method

As with other aspects of an HVAC system, an engineer must choose a method of specification. There are four basic types of specifications for BAS networks:

- **Descriptive.** Calls out the exact properties of the products. Properties could include communication protocols and data transfer rates.
- **Performance.** Tells what result is required and the criteria by which performance will be verified. Allows bidders to propose products to meet the need.
- **Reference standard.** Requires products to conform to an established standard. Does not oblige contractor to meet end user's needs not addressed in the standard.
- **Proprietary.** Calls out brand names. May be necessary in expansion of existing systems.

Writing a descriptive network specification requires knowledge of the details of network technology. To succeed with any specification, the designer must articulate the end user's needs. Typically, performance-based specification is the best value for the customer (Ehrlich and Pittel 1999).

Communication Tasks

Determining network performance requirements means identifying and quantifying the communication functions required. Ehrlich and Pittel (1999) identified the following five basic communication tasks necessary to establish network requirements.

Data Exchange. What data passes between which devices? What control and optimization data passes between controllers? What update rates are required? What data does an operator need to reach? How much delay is acceptable in retrieving values? What update rates are required on "live" data displays? (Within one system, answers may vary according to data use.) Which set points and control parameters do operators need to adjust over the network?

Alarms and Events. Where do alarms originate? Where are they logged and displayed? How much delay is acceptable? Where are they acknowledged? What information must be delivered along with the alarm? (Depending on system design, alarm messages may be passed over the network along with the alarms.) Where are alarm summary reports required? How and where do operators need to adjust alarm limits, etc.?

Schedules. For HVAC equipment that runs on schedules, where can the schedules be read? Where can they be modified?

Trends. Where does trend data originate? Where is it stored? How much will be transmitted? Where is it displayed and processed? Which user interfaces can set and modify trend collection parameters?

Network Management. What network diagnostic and maintenance functions are required at which user interfaces? Data access and security functions may be handled as network management functions.

Bushby et al. (1999) refer to the same five communication tasks as **interoperability areas** and list many more specific considerations in each area. ASHRAE *Guideline* 13 also provides more detailed information that is helpful.

APPROACHES TO INTEROPERABILITY

Many approaches to interoperability have been proposed and applied, each with varying degrees of success under various circumstances. The field changes quickly as product lines emerge and standards develop and gain acceptance. The building automation world continues to evaluate options project by project.

Typically, an interoperable system uses one of two approaches: standard protocols or special-purpose gateways. With a standard, the supplier is responsible for compliance with the standard; the system specifier or integrator is responsible for interoperation. With a gateway, the supplier takes responsibility for interoperation. Where the job requires interoperation with existing equipment, gateways may be the only solution available. Bushby (1998) addressed this issue and some of the limitations associated with gateways. To date, interoperability by any method requires solid field engineering and capable system integration; the issues extend well beyond the selection of a communication protocol.

Standard Protocols

Table 2 lists some applicable standard protocols that have been used in BAS. Their different characteristics make some more suited to particular tasks than others. PROFIBUS (www.profibus.com) and MODBUS (www.modbus.org) were designed for low-cost industrial process control and automated manufacturing applications, but they have been applied to BAS. LonTalk defines a LAN

Table 2 Some Standard Communication Protocols Applicable to BAS

Protocol	Definition
BACnet®	ANSI/ASHRAE *Standard* 135-2004, EN/ISO *Standard* 16484-5:2003
LonTalk	ANSI/CEA *Standard* 709.1
PROFIBUS FMS	EN 50170:1996 Volume 2
Konnex	EN 50090
MODBUS	Modbus Application Protocol Specification V1.1

technology but not messages that are to be exchanged for BAS applications. BACnet® or implementers' agreements, such as those made by members of LonMark International, are necessary to achieve interoperability with LonTalk devices. Konnex evolved from the European Installation Bus (EIB) and several other European protocols developed for residential applications, including multifamily housing.

BACnet is the only standard protocol developed specifically for commercial BAS applications. BACnet has been adopted as a national standard in the United States, Korea, and Japan, as a European standard, and as a world standard (EN/ISO *Standard* 16484-5). BACnet was designed to be used with a variety of LAN technologies and also defines a way to connect BACnet devices with Konnex devices.

Gateways and Interfaces

Rather than conforming to a published standard, a supplier can design a specific device to exchange data with another specific device. This typically requires cooperation between two manufacturers. In some cases, it can be simpler and more cost-effective than for both manufacturers to conform to an agreed-upon standard. The device can be either custom-designed or off the shelf. In either case, the communication tasks must be carefully specified to ensure that the gateway performs as needed.

Choosing a system that supports a variety of gateways may be a way to maintain a flexible position as products and standards continue to develop.

SPECIFYING DDC SYSTEMS

Successful DDC installation depends in part on a clear description (specification) of what is required to meet the customer's needs. The specification should include descriptions of the products desired, or of the performance and features expected. Needed points or data objects should be listed. A control schematic shows the layout of each system to be controlled, including instrumentation and input/output objects and any hard-wired interlocks. A sequence of operation should be provided for each system. Additional information on specifying DDC controls can be found in ASHRAE *Guideline* 13. ASHRAE (2005) provides sample sequences of control for air-handling systems.

COMMISSIONING

A successful control system requires a proper start-up and testing, not merely the adjustment of a few parameters (set points and throttling ranges) and a few quick checks. With the services of an experienced control professional, the typical DDC system can be used effectively in the commissioning process to test and document HVAC system performance. In general, increased use of VAV systems and digital controls has increased the importance of and need for commissioning.

Design and construction specifications should include specific commissioning procedures. In addition, commissioning should be coordinated with testing, adjusting, and balancing (TAB) because each affects the other. The commissioning procedure begins by checking each control device to ensure that it is installed and connected according to approved drawings. Each electrical and pneumatic connection is verified, and all interlocks to fan and pump motors and primary heating and cooling equipment are checked. Chapter 42 of the 2007 *ASHRAE Handbook—HVAC Applications* and ASHRAE *Guideline* 1 explain how commissioning starts with project conception and continues for the life of the building.

TUNING

Systematic tuning of controllers improves performance of all controls and is particularly important for digital control. First, the controlled process should be controlled manually between various set points to evaluate the following questions:

- Is the process noisy (rapid fluctuations in controlled variable)?
- Is there appreciable hysteresis (backlash) in the actuator?
- How easy (or difficult) is it to maintain and change set point?
- In which operating region is the process most sensitive (highest gain)?

If the process cannot be controlled manually, the reason should be identified and corrected before the controller is tuned.

Tuning optimizes control parameters that determine steady-state and transient characteristics of the control system. HVAC processes are nonlinear, and characteristics change seasonally. Controllers tuned under one operating condition may become unstable as conditions change. A well-tuned controller (1) minimizes steady-state error for set point, (2) responds quickly to disturbances, and (3) remains stable under all operating conditions. Tuning proportional controllers is a compromise between minimizing steady-state error and maintaining margins of stability. Proportional plus integral (PI) control minimizes this compromise because the integral action reduces steady-state error, and the proportional term determines the controller's response to disturbances.

Tuning Proportional, PI, and PID Controllers

Popular methods of determining proportional, PI, and PID controller tuning parameters include closed- and open-loop process identification methods and trial-and-error methods. Two of the most widely used techniques for tuning these controllers are ultimate oscillation and first-order-plus-dead-time. There are many optimization calculations for these two techniques. The Ziegler-Nichols, which is given here, is well established.

Ultimate Oscillation (Closed-Loop) Method. The closed-loop method increases controller gain in proportional-only mode until the equipment continuously cycles after a set-point change (Figure 22, where $K_p = 40$). Proportional and integral terms are then computed from the cycle's period of oscillation and the K_p value that caused cycling. The ultimate oscillation method is as follows:

1. Adjust control parameters so that all are essentially off. This corresponds to a proportion band (gain) at its maximum (minimum), the integral time (repeats per minute) or integral gain to maximum (minimum), and derivative to its minimum.
2. Adjust manual output of the controller to give a measurement as close to midscale as possible.
3. Put controller in automatic.
4. Gradually increase proportional feedback (this corresponds to reducing the proportional band or increasing the proportional gain) until observed oscillations neither grow nor diminish in amplitude. If response saturates at either extreme, start over at Step 2 to obtain a stable response. If no oscillations are observed, change the set point and try again.
5. Record the proportional band as PB_u and the period of oscillations as T_u.
6. Use the recorded proportional band and oscillation period to calculate controller settings as follows:

Proportional only:

$$PB = 1.8(PB_u) \quad \text{percent} \tag{4}$$

Proportional plus integral (PI):

$$PB = 2.22(PB_u) \quad \text{percent} \tag{5}$$

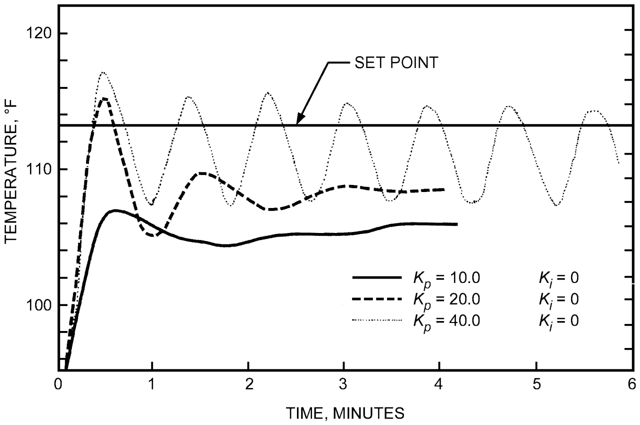


Fig. 22 Response of Discharge Air Temperature to Step Change in Set Points at Various Proportional Constants with No Integral Action

$$T_i = 0.83T_u \quad \text{minute per repeat} \tag{6}$$

Proportional plus integral plus derivative (PID):

$$\text{PB} = 1.67(\text{PB}_u) \quad \text{percent} \tag{7}$$

$$T_i = 0.50T_u \quad \text{minute per repeat} \tag{8}$$

$$T_d = 0.125T_u \quad \text{minute} \tag{9}$$

First-Order-plus-Dead-Time (Open-Loop) Method. The open-loop method introduces a step change in input into the opened control loop. A graphical technique is used to estimate the process transfer function parameters. Proportional and integral terms are calculated from the estimated process parameters using a series of equations.

The value of the process variable must be recorded over time, and the dead time and time constant must be determined from it. This can be accomplished graphically as seen in Figure 23. The first-order-plus-dead-time method is as follows:

1. Adjust controller manual output to give a midscale measurement.
2. Arrange to record the process variable over time.
3. Move the manual output of the controller by 10% as rapidly as possible to approximate a step change.
4. Record the value of the process variable over time until it reaches a new steady-state value.
5. Determine dead time and time constant.
6. Use dead time (TD) and time constant (TC) values to calculate PID values as follows:

$$\text{Gain} = \frac{\text{\% change in controlled variable}}{\text{\% change in control signal}} \tag{10}$$

Proportional only:

$$\text{PB} = \text{Gain}/(\text{TC}/\text{TD}) \tag{11}$$

Proportional plus integral (PI):

$$\text{PB} = 0.9(\text{Gain})/(\text{TC}/\text{TD}) \tag{12}$$

$$T_i = 3.33(\text{TD}) \tag{13}$$

Proportional-integral-derivative (PID):

$$\text{PB} = 1.2(\text{Gain})/(\text{TC}/\text{TD}) \tag{14}$$

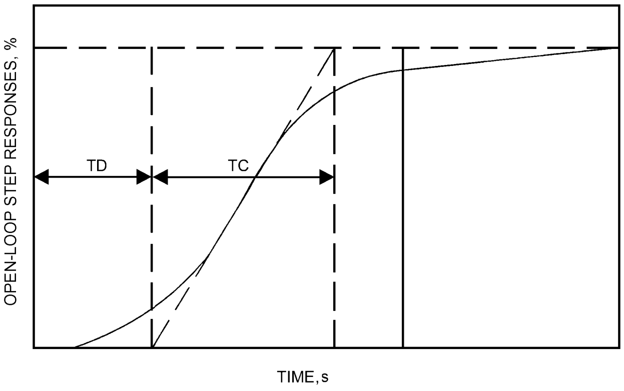


Fig. 23 Open-Loop Step Response Versus Time

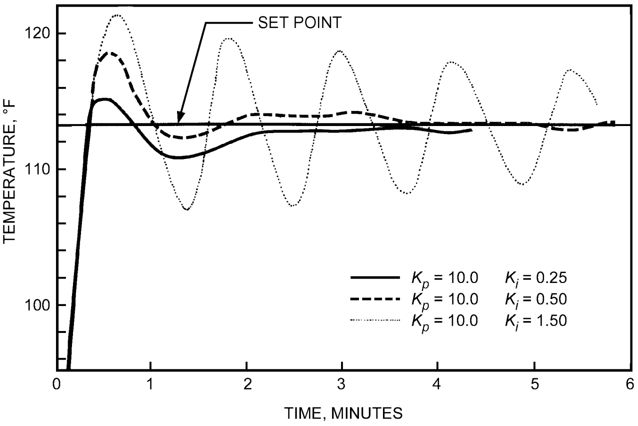


Fig. 24 Response of Discharge Air Temperature to Step Change in Set Points at Various Integral Constants with Fixed Proportional Constant

$$T_i = 2(\text{TD}) \tag{15}$$

$$T_d = 0.5(\text{TD}) \tag{16}$$

Trial and Error. This method involves adjusting the gain of the proportion-only controller until the desired response to a set point is observed. Conservative tuning dictates that this response should have a small initial overshoot and quickly damp to steady-state conditions. Set-point changes should be made in the range where controller saturation, or output limit, is avoided. The integral term is then increased until changes in set point produce the same dynamic response as the controller under proportional control, but with the response now centered about the set point (Figure 24).

Tuning Digital Controllers

In tuning digital controllers, additional parameters may need to be specified. The digital controller sampling interval is critical because it can introduce harmonic distortion if not selected properly. This sampling interval is usually set at the factory and may not be adjustable. A controller sampling interval of about one-tenth of the controlled-process time constant usually provides adequate control. Many digital control algorithms include an error dead band to eliminate unnecessary control actions when the process is near set point. Hysteresis compensation is possible with digital controllers, but it must be carefully applied because overcompensation can cause continuous cycling of the control loop.

Computer Modeling of Control Systems

Each component of a control system can be represented by a transfer function, which is an idealized mathematical representation of the relationship between the input and output variables of the component. The transfer function must be sufficiently detailed to cover both the dynamic and static characteristics of the device. The dynamics are represented in the time domain by a differential equation. In environmental control, the transfer function of many of the components can be adequately described by a first-order differential equation, implying that the dynamic behavior is dominated by a single capacitance factor. For a solution, the differential equation is converted to its Laplace or z-transform. Some energy simulation programs are capable of modeling various control strategies.

For more information on programs, see Chapter 39 of the 2007 *ASHRAE Handbook—HVAC Applications*.

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