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3.1 Controllers—Pneumatic


**Types:**
Receiver controllers: Indicating, recording, miniature, high-density miniature, and large case.

Direct-connected controllers:
Blind, indicating, or recording, in large or medium case for field or panel mounting.

**Application:**
Receiver controllers: Control of any variable that can be measured and translated into an air pressure by a pneumatic transmitter; includes automatic and manual control and set point adjustment.

Direct-connected controllers:
Have own measuring element in contact with the process; measuring elements available include pressure, differential pressure, temperature, level, pH, thermocouple, radiation pyrometer, and humidity.

**Typical Front Panel Size:**
Miniature: 6 in. × 6 in. (150 mm × 150 mm)
High-density miniature: 3 in. × 6 in. (75 mm × 150 mm)
Large case: 15 in. × 20 in. (375 mm × 500 mm)

**Minimum Response Level:**
Less than 0.01% of full scale

**Input Range (measurement):**
3 to 15 PSIG (0.2 to 1.0 bar) or direct-connected

**Output Range (signal to valve):**
3 to 15 PSIG (0.2 to 1.0 bar)

**Repeatability:**
± 0.2% of span

**Inaccuracy:**
± 0.25 to 2% of span

**Displays:**
Set point, process variable (measurement), controlled variable (output to control valve), deviation, and balance

**Maximum Frequency Response:**
Flat to 30 Hz

**Maximum Zero Frequency Gain:**
750

**Control Modes:**
Manual, on-off, proportional (P), integral (I-reset), derivative (D-rate), floating, differential gap, follow-up, cascade

**Costs:**
Direct-connected, indicating, field-mounted controller costs range from $500 to $2000; miniature indicating controller costs $1000 to $2500; miniature high-density indicating controller indicating $1500 to $2500; miniature recording controller costs
Partial List of Suppliers:

- ABB Group (www.abb.com)
- Ametek (www.ametek.com)
- Barton (www.barton-instruments.com/index2.php)
- Bristol Babcock (www.bristolbabcock.com)
- Emerson Process Management (www.emersonprocess.com)
- Foxboro Co. (www.foxboro.com/m&i/specifications/controllers/)
- Honeywell Automation and Control (hbctradeline.honeywell.com/Catalog/Pages/default.asp)
- Leslie Controls, Inc (www.lesliecontrols.com)
- Powers Process Controls (www.powerscontrols.com)
- Samson AG (www.samson.de/pdf_en/_ek16_re.htm)
- Trautomation (www.trautomation.com/automation/categorie.nsf/)

3.1 Controllers—Pneumatic

$2000 to $3000; large-case indicating controller costs $1500 to $2500; and large-case recording controller costs $2000 to $3000

**HISTORY AND DEVELOPMENT**

Pneumatic controllers were first introduced at the turn of the twentieth century. They logically followed the development of diaphragm-actuated valves in the 1890s. Early types were all direct connected, local mounting, indicating, or blind types. Large-case indicating and circular chart recording controllers appeared around 1915. All early models incorporated two-position, on/off action or proportional action. It was not until 1929 that reset action was introduced. Rate action followed in 1935.

Until the late 1930s, all controllers were direct connected and therefore had to be located close to the process. Pneumatic transmitters were not introduced until the later 1930s. To make them compatible, the large-case pressure recording and indicating controllers were easily converted into receiver controllers. This made remote mounting practicable, and centralized control rooms became a reality. Because of the inherent advantages, the combination of pneumatic transmitters and receiver controllers quickly became popular. Since the recording and indicating receiver controllers were quite large, control rooms and panel boards were likewise spacious. Additionally, all control boards had a monotonous look and usually came in one color—black.

A revolution in design occurred in 1948 with the introduction of miniature instruments. Here the concept of the controller evolved into a combination of a small, approximately 6 in. × 6 in. (150 mm × 150 mm), panel front indicating and recording control station and a blind receiver controller. The station permitted the operator to monitor the measured variable (process variable), set point, and valve output; it allowed the operator to switch between, and operate in, either the automatic or manual control modes.

Miniature controllers ushered in the era of the graphic panel, in which the instruments are inserted into graphic symbols representing the attendant process apparatus. Control rooms became more compact, control boards more meaningful and colorful, and because operators quickly developed a “feel” for the process, training time was considerably reduced.

Nevertheless, graphic panels were also wasteful of space and presented major modification problems each time the process was changed. This led to the evolution of the semi-graphic panel, in which a graphic symbol diagram of the process appeared above the miniature instruments mounted in neatly spaced rows and columns.

In 1965, miniature, high-density mounting style stations appeared. The new lines brought with them the most advanced ideas in displays, operating safety and simplicity, packaging, installation simplicity, and servicing facility. Along with some of the standard miniature controllers, they offered computer compatibility along with some unique control capabilities that had previously been impractical.

The early 1980s saw some important new entries in the pneumatic controller market. These included pneumatic controllers using RTD and thermocouple type sensors and pneumatic controllers with microprocessor-based serial communication modules for tie-in to distributed control systems.

As first analog (Section 3.2), and later digital electronic (Section 4.4) and DCS-based software controllers (Chapter 4) became available, they gradually took over the controller marketplace, but pneumatic units are still used in many existing plants and in locations where intrinsic safety is essential.

**OPERATING PRINCIPLES**

There are both force and motion balance pneumatic controllers. A receiver-type pneumatic controller based on the force balance principle (moment-balance) is shown schematically in Figure 3.1a. A process transmitter (lower left) senses the measured variable (i.e., process variable, e.g., pressure, temperature, flow) and transmits a proportional air pressure to the measured variable (MV) bellows of the controller.
The controller compares the measured variable against the set point (SP) and sends a corrective air signal (error or deviation) to manipulate the control valve, thereby completing the feedback control loop.

Figure 3.1a depicts a so-called direct acting controller; the output of the controller increases when the measured variable increases. The controller action is selected as a function of the failure position of the control valve and the relationship between the controlled and manipulated variables. To illustrate this relation with an example, visualize a process cooler. The purpose of the control loop on that cooler is to maintain the temperature at the outlet of the cooler. If the cooling water valve fails closed, a rise in the detected temperature will require further opening of the coolant valve, which means that the air signal to the valve should drop and therefore the controller has to be reverse acting.

In Figure 3.1a, the controller consists of two sets of opposed bellows of equal area, acting at opposite ends of a force beam that rotates about a movable pivot. Extending from the right end of the beam is a flapper that baffles the detector nozzle of the booster relay.

**Booster Circuit**

Supply air connects to the pilot valve of the booster and flows through a fixed restriction into the top housing and out the detector nozzle. The flapper is effective in changing the backpressure on the nozzle as long as the clearance is within one-fourth of the nozzle diameter. The restriction size is selected on the basis that the continuous air consumption will be reasonable and that it will be large enough not to clog with typical instrument air. The nozzle, on the other hand, must be large enough that when the flapper has a clearance of one-fourth nozzle diameter, nozzle backpressure drops practically to atmospheric. It must not be so large, however, that the seating of the flapper becomes too critical.

A typical size of restriction is 0.012 in. ID (0.3 mm) while the nozzle would be 0.050 in. ID (1.3 mm). The nozzle backpressure is a function of flapper position. (For a more detailed discussion of circuits, refer to Section 1.4, “Electronic versus Pneumatic Instruments.”)

The exhaust diaphragm senses nozzle backpressure and acts on the pilot valve. If the backpressure increases, it pushes down on the valve, opening the supply port to build up the underside pressure on the diaphragm until it balances the nozzle backpressure. If the backpressure decreases, the diaphragm assembly moves upward, allowing the valve to close off the supply seat while opening an exhaust seat in the center of the diaphragm. This allows the underside pressure to exhaust through the center mesh material of the diaphragm assembly until the pressures balance.

**Proportional Response**

Since a pressure range of 3 to 15 PSIG (0.2 to 1.0 bar) is an almost universal standard for representing 0 to 100% of the range of a measured variable, a set point, and the output of receiver controllers, this description will assume the operation to be in this range.
To understand the proportional response, first assume that the derivative needle valve is wide open and that the reset needle valve is closed with 9 PSIG (0.6 bar) mid-scale pressure, trapped in the reset bellows R (Figure 3.1a). If the set point is adjusted to 9 PSIG (0.6 bar), when the measured variable equals set point, the flapper will automatically be positioned so that the booster output, acting on the feedback bellows (FB), will be equal to the reset pressure, namely 9 PSIG (0.6 bar). The reason for this is that the force beam will only come to equilibrium when all of the moments cause a rotation of the beam with attendant repositioning of the flapper and change in feedback pressure until the moment balance is restored.

If the pivot is positioned centrally, where moment arm A equals B, then for every 1 PSI (0.067 bar) difference between set point and measured variable there will be a 1 PSI (0.067 bar) difference between reset and controller output, or feedback. This represents a 100% proportional band setting, or a gain of one. Percent proportional band is defined as the input change divided by the output change times 100. Gain equals the ratio of output change to input change. For a description of both the proportional band and of controller action, refer to Figure 3.1b.

\[
\text{PB} \% = \frac{\text{change in input}}{\text{change in output}} \times 100 \quad 3.1(1)
\]

\[
\text{gain} = \frac{\text{output change}}{\text{input change}} = 100/\text{PB} \quad 3.1(2)
\]

If the pivot in Figure 3.1a is shifted to the right, to the point where moment arm A is four times greater than moment arm B, then every 1 PSI (0.067-bar) change in the measured (also called controlled) variable results in a 4-PSI (0.27-bar) change in the output (also called manipulated) variable. This gives a proportional band of 25%, or a gain of four.

If the pivot is moved to the left, the ratio is reversed and the proportional band would be 400%, which corresponds to a gain of 0.25. If the pivot could be moved to the right to coincide with the center of the R and FB bellows, the most sensitive setting would be achieved, i.e., approaching 0% band or infinite gain. In this state, the slightest difference between MV and SP would rotate the flapper to change the output to 0 PSI (0 bar) or full supply pressure, depending upon the action of the error (on/off control).

**Reset or Integral Response**

If it were practical to use a 1 or 2% proportional band on all processes, proportional action alone would be sufficient for most processes. However, most process loops become unstable at such or even wider bands. Flow control loops, for example, usually require more than a 200% band for stability. Assuming that the process cannot tolerate a band narrower than 50%, in that case (Figure 3.1b), the controller can maintain the measured variable on set point only when valve pressure is 9 PSIG (0.6 bar).

If the valve pressure has to be 5 PSIG (0.3 bar), it can only occur when the measured variable deviates from set point by 2 PSI (0.14 bar) (a 16.7% of full scale error). In most cases this amount of error, more correctly termed offset, is intolerable. Nevertheless, in real control systems the valve pressure must change as the load changes.

If the load is such as to require a 5-PSIG (35-kPa) valve pressure, one way of eliminating the offset would be to manually change the reset pressure R to 5 PSIG. The output or valve pressure would then be 5 PSIG when the error is zero. Initially, when proportional-only controllers were used, such manual reset was used, but that is totally unacceptable today.

It is a simple matter to make this reset action automatic. It only requires that the reset bellows be able to communicate with the controller output pressure through some adjustable restriction such as a needle valve. The reset action must be tuned to the process in such a way as to allow the process sufficient time to respond. Too fast a reset speed, in effect, makes the controller “impatient” and results in instability. Too slow a speed results in stable operation, but the offset is permitted to persist for a longer period than necessary.

To describe the automatic reset action, assume that set point is at 9 PSIG (0.6 bar) and the reset is trapped at 9 PSIG, while valve pressure feedback, because of load change, must be at 5 PSIG (0.3 bar). According to Figure 3.1b, with the proportional band at 50%, the measured variable will be controlled at 7 PSIG (0.46 bar).
If the reset needle valve is then opened slightly, the pressure in the reset bellows will gradually decrease. As it drops from 9 to 7 PSIG (0.6 to 0.46 bar), the measured variable pressure will rise from 7 to 8 PSIG (0.46 to 0.5 bar). The reset pressure will continue to drop until it exactly equals output, i.e., 5 PSIG (0.3 bar). At this point, the measured variable will exactly equal set point, 9 PSIG (0.6 bar). With this configuration, regardless of where the valve pressure must be, the controller will ultimately provide the correct valve pressure with no offset between set point and measured variable.

Reset action can also be understood by looking at it from the controller design perspective. We can see that the controller cannot come to equilibrium as long as there is any difference in pressure between reset and feedback. This is because if there is, the open communication through the reset needle valve will cause the reset to continue to change, which in turn directly reinforces the feedback pressure.

Reset and feedback, in turn, cannot be equal unless the set point and the measured variable are equal to each other. This fact alone ensures that the controller will maintain corrective action until it makes the measured variable exactly equal to set point regardless of where feedback must be. Referring to Figure 3.1b, reset in effect shifts the proportional band lines along a horizontal axis at set-point level. It makes the middle of the band coincide with the required valve pressure.

Reset time is the time required for the reset action to produce the same change in output that the proportional action would if the error remained constant (the available integral time settings range from 0.01 to 60 minutes per repeat). For example, if the response to an error of a plain proportional controller is a 1-PSI (0.067-bar) change in its output and the error is sustained, the integral mode with a 1 minute/repeat reset setting will require 1 minute to eliminate that offset. The integral setting can have the units of either time/repeat or repeats/unit of time.

**Derivative Response**

If a needle valve is inserted between the booster output and the feedback bellows as in Figure 3.1a, it delays the rebalancing action of the feedback bellows and causes the controller to give an exaggerated response to changes in the measured variable. The degree of exaggeration is in proportion to the speed or rate at which the measured variable is changing. (The term derivative action refers to the slope or the rate of change.)

Derivative or rate action is particularly effective in the control of slow processes, such as in temperature control loops. It compensates for lag or inertia. For a sudden change of even small magnitude, it provides an extra “kick” to the control valve. This is because the derivative mode assumes that upsets will continue at the rate they are occurring and corrects right away for the error that would evolve one derivative time later. Conversely, when the error is dropping as the controlled process variable is returning to set point, the rate action anticipates that the inertia of the process will carry it below the set point and begins cutting back the valve response accordingly.

The method shown in Figure 3.1a for adding derivative action to the has some serious limitations. If the derivative needle valve is located as shown, the derivative action will interact with both the proportional and the integral responses and, in fact, will follow the proportional response. This design therefore is useless in preventing overshoot on startup or when large upsets occur, and this derivative also interacts with set point changes. Therefore an independent derivative unit is needed, as shown in Figure 3.1e and described later.

Derivative action can be viewed as if it temporarily changed the proportional band and therefore temporarily changed the slope of the lines in Figure 3.1b. If the error is rising, the change is clockwise; if it is dropping, the change is counterclockwise; if the error is constant, no change occurs. Derivative time is the amount of time (usually in minutes) by which the rate action anticipates into the future and leads the feedback pressure during a steady ramp input change. (Derivative settings can usually be adjusted from 0.01 to 60 minutes.)

**MINIATURE CONTROLLER DESIGNS**

Two designs of force-balance receiver controllers are shown in Figures 3.1c and 3.1d. The controller in Figure 3.1c closely resembles that of Figure 3.1a, except that the bellows all act from one side against a pivoted “wobble plate.” The wobble plate acts as the nozzle’s baffle. Rotating the pivot axis...
Changes the proportional band. When the pivot axis coincides with the reset and feedback bellows, 0% proportional band results; when it coincides with the measured variable and set point bellows, infinite band results. When the axis bisects the two bellows’ axis, 100% proportional band results. Otherwise, the operation is the same as described for Figure 3.1a.

The controller in Figure 3.1d is constructed of machined aluminum rings, which are separated by rubber diaphragms with bolts holding the assembly together. The lower portion of the controller forms the booster section. This is quite similar to the booster in Figure 3.1a.

The detector section consists of three diaphragms. The upper and lower diaphragms have equal areas, while the center diaphragm has half the effective area of the other two. Reset pressure acts in the top chamber. Assume this pressure is at mid-scale and that the reset needle valve is closed. The reset pressure acts on the top diaphragm, which is part of a 1:1 repeating relay. Supply air passes through a restriction and out the exhaust nozzle. The diaphragm baffles the nozzle to make the backpressure equal to the reset pressure.

Assume further that the proportional band needle valve is closed. The pressure then acting on top of the detector section will be the reset pressure as reproduced by the 1:1 relay since the two chambers are connected via a restriction. If the measured variable signal equals the set point, the detector diaphragm assembly, with its integral nozzle seat, will baffle the nozzle so as to make the controller output, or valve pressure, equal to the reset pressure, thus balancing all of the forces acting on the detector.

If the measured variable is then increased by 1 PSI (0.067 bar), the increase in pressure acts downward on the lower diaphragm as well as upward on the center diaphragm. The net effect is the same as having the pressure act downward on a diaphragm of half the area of the lower diaphragm. Since the output pressure acts upward on the full area of the lower diaphragm, it needs to increase only 1/2 PSI (0.03 bar) to bring the forces to balance. Since a 1-PSI (0.067-bar) change in input resulted in a 1/2-PSI change in output, the proportional band is said to be at 200% or the gain is said to be 0.5.

If the proportional band needle valve were wide open, so that it provided negligible resistance, then if the measured variable pressure increased ever so slightly above set point, the full effect of the resultant change in output would be felt on top of the detector stack. This would cause the output to increase further, which in turn would feed upon itself, and the action would continue to regenerate until the output reached its maximum limit. Therefore, with the proportional band needle valve wide open, the narrowest proportional band is obtained.

If the proportional band needle valve is set to where its resistance equals that of the restriction separating the reproducing relay from the top of the detector section, then the following action results. If the measured variable deviates from set point by 1 PSI (0.067 bar) in an increasing direction, instantly the output will rise 1/2 PSI (0.03 bar) because of the construction of the detector section. The difference in pressure between the controller output and the reproducing relay will cause a flow through the reset needle valve and the intermediate restriction.

Since the resistance of the two is equal, the pressure drop will divide equally, causing a 1/4-PSI (0.017-bar) increase on the top of the detector section. This 1/4-PSI increase directly causes the output to increase 1/4 PSI, which further causes the pressure on top of the detector to increase by 1/8 PSI (0.008 bar). The action continues until equilibrium is obtained, with the output having changed a total of 1 PSI (0.067 bar) and with the pressure on top of the detector section having increased 1/2 PSI (0.03 bar). Since a 1-PSI change in variable resulted in a 1-PSI change in output, this needle valve opening provides a 100% proportional band.

The reset action in this controller is similar to that in Figure 3.1a in that any change in reset pressure propagates down through the unit to directly affect the output. The controller will not come to equilibrium until all forces are balanced, i.e., the measured variable will have to equal set point and the reset pressure will have to equal controller output.

**Derivative Relay**

It was noted earlier that the type of derivative circuit used in Figure 3.1a interacted with the effects of the other control modes. Derivative action is more effective if it is noninteracting and if it can be applied ahead of the contributions of the proportional and reset actions of the controller. Such a derivative unit can be built into the controller, or it can be a separate relay as shown in Figure 3.1e. This relay employs diaphragms, but the design can also use bellows.

In this design the signal from some process transmitter is connected to the input port at the top. Because of the difference
Transmitters and Local Controllers

between input and output diaphragm areas, the result of the force balance design is that a step change in input pressure will produce an amplified step change in output pressure.

In a steady-state condition (with no change in input), the output pressure acts on both sides of the output diaphragm — and output pressure rebalances the input pressure directly. The output pressure is connected to the intermediate chamber through the needle valve. There is therefore a lag between a change in output and a change in intermediate pressure.

If the input changes with a continuous ramp, the intermediate pressure will lag the output by a constant amount, proportional to the rate of change in output. Thus, the intermediate pressure will partially rebalance the input, reducing the effective gain. The result is that the output will conti-

FIG. 3.1e
Direct and inverse derivative relays.

nuously lead the input by a definite amount, which is proportional to the rate of change in input. The time by which the output leads the input is the “derivative time.” The graduated needle valve is used to set the derivative time.

An inverse derivative relay is also shown in Figure 3.1e. It works in the opposite manner and thereby attenuates high-frequency signals. It can therefore serve as a noise filter and stabilizing relay on “noisy” processes.

Miniature Control Stations

Miniature control stations with a panel face of nominally 6 in. × 6 in. (150 mm × 150 mm) and inserted into individual cutouts having approximately 10 in. (250 mm) center-to-center distances are one of the common types found on central control room panels in the various process industries. Figure 3.1f shows a typical cross section of some of the types of units available.

FIG. 3.1f
Types of miniature pneumatic controllers. (a) Typical indicating control station. (b) Indicating control station with 12 o’clock scanning features. (c) Recording control station with 30-day strip-chart and vertical moving pen. (d) Recording control station with horizontal moving pen and daily chart tear-off feature. (e) Indicating control station with two duplex vertical scale indicators (f) Recording control station with no “seal” position. (g) Recording control station with servo-operated pen. (h) Recording control station with procedureless switching. (i) Indication control station with instant procedureless switching.

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The interconnections of an indicating miniature control station are shown in Figure 3.1g. The measured variable is indicated on the center pointer, and the set point is indicated on the peripheral pointer of a duplex gauge. On automatic, the operator changes the set point by adjusting the set point regulator and noting the set point on the gauge.

The controller is connected to the control valve via the manual–automatic switch. The controller compares the measured variable with the set point and manipulates the control valve to bring the variable on set point. If the operator wishes to switch to manual, he or she notes the valve pressure by operating the upper left-hand switch on the station. Next, the operator turns the right-hand switch to “seal,” which isolates the controller from the control valve. After that, the operator adjusts the regulator to match the noted valve pressure and then turns the right-hand switch to the manual position, which connects the regulator directly to the valve. In manual, the operator directly adjusts the valve, while the controller reset follows the changes that are made to the valve.

In switching back to automatic, the operator goes to “seal” position and adjusts the set point regulator to match the measured variable. If the set point and measured variable are equal at switchover, and if the reset is equal to the valve pressure, the controller output should then equal the valve pressure, and the switchover is effected without a “bump.”

**Four-Pipe System** Since a lag exists in the transmission of pneumatic signals, the dynamic capability of a control loop can be affected by increasing the distance between the controller and the process. Transmission lag will interfere with the performance of fast control loops such as liquid flow control but will not be significant if the distance is up to 100 ft (30 m).

For control loops where the transmission lag cannot be tolerated, the controller can be mounted locally, near the measuring transmitter and control valve, as shown in Figure 3.1h.

In this design, four air signal tubes are run between the control station and the field-mounted equipment. These carry the measured variable, set point, valve pressure, and relay operating pressure lines. Hence, the name “four-pipe system,” whereas the configuration in Figure 3.1g is referred to as a “two-pipe system.” Since the lines going back to the station amount to dead-ended parallel connections, the dynamics of
the control loop are the same as they would be with any closed-loop system.

In switching from automatic to manual, the operator switches the loop to the “seal” position, which actuates the cutoff relay, to isolate the controller from the valve and permits the operator to change the set point regulator to match the noted valve pressure. This pressure is then connected to the valve when the operator turns the switch to manual. Returning to automatic involves the same procedure as was described for Figure 3.1g.

The disadvantages of this circuit are that:

1. It is more costly to run four transmission tubes between the control station and the field-mounted equipment.
2. The controller settings cannot be adjusted from the control panel.

**Effect of Transmission Distance** Since there is a transportation lag caused by pneumatic transmission, control is affected as the distance between the process and controller increases. Figure 3.1i shows the effect of increasing transmission distance between the process and the controller. As can be seen, a 10% upset in liquid flow will result in longer and longer recovery times as the transmission distance increases. Since liquid flow control is one of the fastest processes, this amounts to a worst-case example; the effect on slower processes will be proportionately less.

From the charts it can be seen that with all instruments closed-coupled it took 8 seconds for the system to recover. At a transmission distance of 250 ft (75 m), the recovery time was still approximately 8 seconds. At 500 ft (150 m), it was 16 seconds, and at 1000 ft (300 m), 37 seconds. These results were obtained using 1/4 in. (6 mm)-OD tubing, which is conventional.

When 3/8 in. (9 mm) tubing was used, there was a significant improvement. At 1000 ft (300 m), the recovery time was reduced from 37 to 27 seconds. An equivalent electronic control loop had an 8-second recovery time. The upper, noisy record on the charts (b), (c), (d), and (e) is a plot of the flow as it was recorded at the transmitter. The lower, smoother records are the flows as they appeared on the remotely located recorder-controller.

If this lag is objectionable, the four-pipe system shown in Figure 3.1h can be used, and if it was, the dynamic performance would be equivalent to that of the closed-loop system. Other options include the installation of booster relays in the transmission lines or the use of larger-diameter transmission tubing.

**Remote-Set Stations** If a modification as shown in Figure 3.1j is added to the basic station in Figure 3.1g, the control station can accommodate a remote set point signal from sources such as remote ratio or proportioning relay, primary cascade controller, or computer.

**Computer-Set Station** The addition of a stepping motor to the set point regulator or to the set point motion transmitter as in Figure 3.1k allows the control station to be set from a digital computer. The station provides the option of switching the loop from computer control of the set point to manual, as shown in the Figure. The stepper motor, which operates the regulator, can be driven by time-duration signals or by individual up-down pulses. A resolution of at least 1000 pulses for full scale is provided.
3.1 Controllers—Pneumatic

Single-Station Cascade  Cascade control can be implemented either with two controller stations, with the master controller (such as Figure 3.1g) generating the set point for the slave (or secondary), which is connected as in Figure 3.1j. The other option is to use a single station, such as shown in Figure 3.1l. The latter scheme not only eliminates one of the two stations but also offers operating safety and convenience.

A common problem with having separate master and slave stations is that when the operator switches the slave to manual, he or she often forgets to also switch the master station to manual as well. In such situation, the primary controller has no influence on the manipulated variable and will not be balanced when the loop is returned to cascade. This is particularly undesirable because cascade circuits are usually used on the most critical loops.

In Figure 3.1l, the regulator has three functions:

1. Set point to primary controller in cascade control
2. Set point to secondary controller for independent secondary control
3. Manual valve setting

There is a seal position between each step while the regulator is set for its upcoming function. The key to this station is the concept used in making the secondary measured variable (MV2) the reset feedback of the primary controller while on manual or secondary control. Versions are also available that allow cascade, independent automatic control on the primary and manual modes of operation.

“No Seal” Station  By using two regulators or two motion transmitters in a station (Figure 3.1m), the need for a “seal” position can be eliminated. In this configuration, when the operator wishes to switch to manual, he or she adjusts the manual regulator to match the controller output while viewing a deviation indicator. When the deviation is zero, the operator transfers control.

Procedureless Switching Stations  With procedureless switching, the operator simply turns a switch, and the station automatically takes care of the pressure-balancing requirements. Two designs are shown in Figure 3.1n. The mechanism on the top (a) is a motion transmitter/receiver combination. This motion transmitter provides the set point pressure when the controller is in automatic and the valve pressure when in manual—similarly to the regulator in Figure 3.1g.

As a motion transmitter, a friction clutch holds the index lever at whatever position the operator has set it. A restriction-nozzle circuit senses the position and converts it to a proportional pneumatic output that is fed back to the rebalancing bellows. A 0 to 100% movement of the index gives a 3- to 15-PSIG (0.2- to 1.0-bar) output pressure. When acting as a receiver, supply pressure is cut off from the restriction nozzle circuit and the pressure to be sensed is admitted to the rebalancing bellows.

The friction clutch is disconnected so that the index lever can be moved by the rebalancing bellows. The unit is so designed and calibrated that a 3- to 15-PSIG (0.2- to 1.0-bar) sensed pressure produces a 0 to 100% index movement. Therefore, as the operator moves the switch from automatic
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The index is declutched; supply is cut off from the restriction nozzle circuit; controller output (valve) pressure is admitted to the bellows causing the index level to take a position proportional to the pressure; controller output is disconnected from the valve line; the clutch is engaged; supply pressure is readmitted to the restriction nozzle circuit; and the unit again acts as a motion transmitter, now providing valve pressure.

Switching back to automatic involves the same sequence, in reverse order. This is the same sequence as carried out in Figure 3.1g, except that here it is automatic.

A second system for procedureless switching involves the use of self-synchronizing regulators or synchros (see design b in Figure 3.1n). One regulator provides set point, while the other is used for manual valve loading. As the name implies, this regulator can synchronize itself to some varying pneumatic pressure and thereby provide automatic balancing.

The regulator employs a reaction nozzle circuit that results in very low spring force (approximately 1 oz or 0.28 N) to develop a 3- to 15-PSIG (0.2- to 1-bar) output. The setting spring is adjusted by rotation of a turbine wheel with an integral lead screw (part b in Figure 3.1n). If supply is connected to the comparator controller section, air is transmitted to the increase–decrease nozzles to make the regulator section output match the variable input pressure. If supply is cut off from the comparator controller, the regulator section output remains locked in, with the memory being a function of lead screw position. The unit can then be driven manually by the operator.

When this control station is in automatic, the set point synchro is manually adjusted by the operator, while the valve-operating synchro keeps itself matched to the controller output to allow instant transfer to manual. In manual, the operator adjusts the valve-loading synchro while the set point synchro tracks the measured variable.

In addition to procedureless switching, these stations can also be switched from a remote source, manually or automatically. They can also be gang-switched, and they can be operated in parallel. For example, it is possible to have one station in the central control room and the other out in the field. The operator can use either station and whichever is not in active service keeps itself fully synchronized and ready to take active duty at any instant.

**High-Density Stations**

Miniature high-density stations have a typical panel size of 3 in. × 6 in. (7.5 mm × 150 mm), mount adjacent to each other, and allow very compact and efficient panel arrangements (Figure 3.1o). The units incorporate packaging features that simplify panel construction and design and facilitate servicing. Much of the design is aimed at making the job of the operator simpler, faster, and safer, in line with the present trend to consolidate control rooms, minimize the number of operators, and handle increasingly fast, complex, and critical processes.

**Mid-Scale Scanning Station**

Figures 3.1p, 3.1q, and 3.1r show three types of high-density control stations featuring a mid-scale deviation scanning pointer. The pointer is driven either by a differential detector or differential servo that compares the measured variable against set point. If the two are equal, the red deviation pointer is positioned at mid-scale, where it is screened off by a green scan band. If there is a deviation, the red pointer stands out prominently.

In Figure 3.1p, a fixed, nominal 4 in. (100 mm) vertical scale is employed, and there are separate pointers to indicate set point and measured variable. The station uses the two-regulator approach to achieve “no-seal” switching as in Figure 3.1m. The operator does have to balance pressures before switching, however.
In Figure 3.1q, the station employs an expanded scale, which provides greater readability. The only indication on the scale is deviation, however, and this requires that the set point transmitter scale and deviation servo stay in calibration relative to each other in order to provide an accurate reading of the variable. While the expanded scale gives greater readability, it does have to be moved to bring the reading on scale when the variable makes any excursions.

This station and the one in Figure 3.1r use the two-regulator approach to eliminate the need for a seal position. In both cases the operator balances pressures prior to switch-over. In Figure 3.1q, the operator notes deviation on a ball-in-tube indicator. In Figure 3.1r, the valve switch has a detent action while the indicator switch operates at the mid-throw position, so that the operator moves the integral switch lever back and forth across center while manually matching pressures before switching. The controller in Figure 3.1r is a deviation type actuated by displacement of a deviation link in the indicator circuit. The controller acts to hold the link at its “zero” position.

While thousands of these control stations have been used in control rooms, mid-scale scanning stations have evolved
Transmitters and Local Controllers

into a type combining mid-scale scanning with procedureless switching, using principles described in the next paragraph in connection with Figure 3.1t

**Procedureless Switching Station** Stations shown in Figures 3.1s and 3.1t offer procedureless switching for the operator. Both have a fixed 4 in. (100 mm) scale, separate indication of set point and measured variable, and a scanning technique that allows the set point indicator to overlap the measured variable indicator when the controlled variable is on set point.

The station in Figure 3.1s employs two self-synchronizing regulators or synchros (see Figure 3.1n), one for set point and the other for manual valve loading. When the controller is in automatic, the operator manually adjusts the set point synchro, while the valve-loading synchro automatically tracks controller output. In manual, the operator adjusts the valve-loading synchro while the set point synchro tracks the measured variable. Thus, the station is always balanced allowing for instant transfer of the control mode.

Like its 6 in. × 6 in. (150 mm × 150 mm) counterpart, these stations can also be gang-switched, switched remotely or automatically, and operated in parallel from different locations while maintaining themselves in synchronism, and they are also available in single-station cascade arrangements.

**Motion Transmitter/Receiver** The station in Figure 3.1t employs a dual function motion transmitter/receiver for manual valve loading and valve pressure indication. This unit is similar to that described in Figure 3.1n. In automatic, the index lever is declutched and the feedback capsule, connected to the valve pressure line, moves the index accordingly. In manual, the clutch engages, and the mechanism reverts to a motion transmitter that provides manual valve loading. This allows procedureless switching to manual.

Switching to automatic is also procedureless, assuming that the set point of the process does not change. If the operator wishes the controller to operate at some new value, compared to where the process had been set on manual, the operator must change the set point to that value prior to switching to automatic. However, to facilitate switching to automatic on loops where the set point remains fixed, the station incorporates a separate balancing controller that operates while the station is in manual.

The balancing controller manipulates controller reset pressure to keep the controller output equal to the manual
valve loading even though the measured variable may be off
set point. This allows the operator to switch to automatic
while off the intended set point and yet have the pressures
balanced at switchover and therefore the system to return to
set point without overshoot.

This feature of the circuit is somewhat limited on narrow
proportional band applications, which is usually the case with
slow processes. This is because it takes little deviation from
set point before the reset would have to be at either a vacuum
or considerably above the air supply pressure to obtain the
balance between valve loading and controller output.

**LARGE-CASE DESIGNS**

**Receiver Controllers**

Because of their size, large-case receiver controllers are even
less frequently used as miniature designs. They nevertheless
still find use in some plants and industries where the 24-hour
circular chart is traditional and preferred.

Most large-case controllers operate on a displacement bal-
ance principle. The set point is a mechanical index setting. The
measured variable acts on a pressure spring such as a bellows,
spiral, or helix that moves the recorder pen or indicator pointer.
A differential linkage detects any deviation between the index
and pen position and actuates the flapper-nozzle system in an
effort to bring the deviation down to zero.

One example of a large-case recording controller is shown
in Figure 3.1u. In this design, if the pen moves clockwise, the
differential link moves upward, and the bell-crank moves the
flapper toward the nozzle. The resultant increase in nozzle back-
pressure is reproduced by the relay, whose output is connected
to the control valve and the housing of the proportioning bel-
lows. The pressure increase is transmitted to the small inner
bellows, causing the two connected inner bellows to move to
the right. The spring in the left inner bellows compresses while
the spring in the right distends.

The motion also causes the large right-hand bellows to
move to the right against the housed spring. As the center rod
joining the inner bellows moves to the right, the flapper is
moved back away from the nozzle. This negative feedback
results in proportioning action. The greater this negative feed-
back, the greater the change that will be required in the mea-
sured variable to obtain a given change in the valve. Adjusting
the linkage to change the amount of this negative feedback
changes the proportional band.

Opening the adjustable restriction between the two large
bellows allows flow from the bellows at higher pressure to
the one at lower pressure. In this example, it would flow
from the left to the right bellows, causing the inner bellows
to move left, moving the flapper toward the nozzle and
increasing output further. This action would continue to
regenerate until the pen finally returned to the index, where
full balance would be achieved with the pressure equal in
the two large bellows and with the two inner bellows
centered.

Large-case controllers are also available with remote air-
operated set point adjustment as required in cascade and ratio
control.

**Direct-Connected Controllers**

Direct-connected controllers have their own measuring ele-
ments, which, as the term implies, are directly connected to
the process. They therefore eliminate the need for a transmit-
er. However, the fact that direct-connected controllers must
be located in the vicinity of the process limits their use to
mounting on local control panels. With this design, the pro-
cess connections must be run to the local control panel, which
is costly, troublesome, and hazardous. For these reasons,
these units are seldom used, even on smaller installations and
on local panels.

Direct-connected large-case controllers of the indicating and
recording type predated the receiver type units by some 20 years.
In the first designs, the receiver controllers were direct-con-
ected pressure controllers with a 3- to 15-PSIG range.

The operation of direct-connected large-case controllers
is the same as that of large-case receiver controllers. The pen
or pointer arm, instead of being actuated by pressure from a
process transmitter, is actuated by its own built-in process
pressure detector. The cross sections of some of the measur-
ing elements that are available with large-case controllers are
shown in Figure 3.1v.

These include sensors for the detection of pressure, absolute
pressure, draft, vacuum, differential pressure, liquid level, and
filled systems for temperature measurement. Basic electrical
measurements involved in thermocouples, resistance bulbs,
radiation pyrometers, and pH probes are accommodated in the
potentiometer versions of large-case pneumatic controllers.

As with the large-case receiver controller, the direct-
connected ones are also available with remote set point
adjustment for cascade and ratio control applications.
FIELD-MOUNTED CONTROLLERS

Direct-Connected

Direct-connected controllers mounted in the field are smaller than the large-case instruments. They usually have weather-proof cases and are available in both indicating and blind designs. They can be pipe-mounted, mounted directly on a valve or surface, or flush-mounted on a local panel. They include their own measuring elements. Figure 3.1w shows some typical types and mounting arrangements.

These units are the least expensive pneumatic controllers, and they are expected to be less accurate than the previously discussed designs are. They find use in small local installations and as local field loops in larger plants. Every plant has some noncritical loops that do not require auto–manual switching or the displaying of their controlled variable or access to their set point from the control room. These units are used as local pressure, temperature, and level regulators.

These field-mounted controllers can be had with on/off, differential gap, proportional, reset, and derivative modes of control. Their principles of operation are similar to that discussed in connection with Figures 3.1a and 3.1w.

Receiver-Type

Some field-mounted local controllers receive a signal from a transmitter rather than having their own measuring element. Such controllers are used if the measurement must be transmitted to the control board for recording, alarm, or indication, but the controller is local. Field-mounted receiver controllers are shown in Figures 3.1c and 3.1d. Remote adjustment of set point is also an option with these controllers.

Pneumatic with Electronic Detectors

The temperature controller illustrated in Figure 3.1x, receives a temperature measurement signal from either a thermocouple or a resistance temperature detector (RTD). These indicating pneumatic controllers provide the accuracy, convenience, and range of electrical temperature sensing but without the need for external electrical power. A built-in generator accepts a conventional pneumatic pressure source and produces electrical power for the controller.

The controller compares the process temperature signal with an operator-adjustable set point and delivers a pneumatic control signal to a final control element, which then moves the process temperature towards the set point. Process temperature
and set point are both indicated on this controller. These controllers are available with PI and PID control modes and with or without bumpless and balanceless auto/manual switching.

In some designs, the air supply is also used to generate the required electric power for the unit and therefore, the maximum “instantaneous” air supply requirement could reach 80 SCFH (2.3 normal m$^3$/hr), while the maximum “steady state” air consumption is only 35 SCFH (1.0 normal m$^3$/hr).

In this controller, a thermocouple or RTD temperature sensor signal is applied to the circuit board, which electrically compares the signal with the set point value and acts on the error with its proportional, reset, and rate control modes to restore the process temperature to the set point value.

**SPECIAL PNEUMATIC CONTROLLERS**

**Connections for Digital Highways**

Figure 3.1y illustrates a pneumatic controller, which is provided with microprocessor-based digital highway communication modules for integration into distributed control systems (Figure 3.1y). By thus making it possible to communicate over a data highway, pneumatic controls were made compatible with distributed systems.

The serial communications module reports, upon command, the current value of the set point, process variable, and valve output and the operating mode that the station is in. The communications module can also receive and execute commands, which can change set points or outputs or operating modes. Miniature transducers convert the pneumatic signals to electric, from which the signals are then converted to digital. The serial link operates at 19.2 kilobaud.

The first data highways were introduced in the late 1970s. Fieldbus is an architecture that provides a communication link between all instruments and all computers using a standard interface. Several manufacturers have entered the fieldbus technology market. However, the Internet seriously threatens the fieldbus market, because Web-based communication between instruments and computers may eventually lead to the replacement of some fieldbus components.

**Special Controls**

Feedforward, ratio, cascade, and other loop configurations can be easily implemented with pneumatic hardware. Two of the popular control configurations involve selective and batch...
Selective Control  With automatic selector control, also called override or limit control, two or more control loops are connected to a common valve. In this configuration, when the conditions are normal, the normal controller has command of the valve. However, if some abnormal condition arises, one of the other loops can automatically take over control to keep the plant operation within safe limits.

Unlike safety shutdown systems, here the plant is kept in operation, although its production rate might be cut back as much as necessary to stay within safe limits. When the abnormal condition abates, the normal loop resumes control. Figure 3.1z shows a control system that can be used on a booster pump station that is serving a transcontinental pipeline.

Under normal conditions the discharge pressure of the pump is being controlled. If the suction pressure gets too low, however, as would be the case if the booster pump upstream failed or if a line rupture occurred, the discharge controller would open the valve wide, which would lower the suction pressure beyond safe limits, causing cavitation, which could seriously damage the pump.

To protect against this, a suction pressure controller is added, which is set to the low safe limit, and a low-pressure selector is installed on the two controller outlets. Since the control valve is air-to-open, the low selector chooses the output of that controller, which is asking for the valve to be less open. Under normal conditions, when the suction pressure is adequate, the output of the discharge pressure controller will be the lower and hence, it will throttle the valve. If suction pressure drops to the set point of the suction pressure controller, it automatically takes over control.

A key requirement for correct implementation of this system is to provide both controllers with a live reset feedback from the valve pressure. In this way the controlling unit has its reset acting normally while the standby controller is prevented from saturating or winding up. This way, when either controller takes over, its reset will exactly match the pressure of the signal reaching the valve at the instant of switchover.

Batch Control  Figure 3.1aa shows a control system for batch pressure control. Batch control is special because when a batch is completed and the manual valve is closed while the controller is in automatic, the reset mode of the controller will keep integrating the error until the controller saturates (winds up).

At the next startup, if the controller is PI only, or if it is a PID controller but its derivative mode is interacting with the proportional and reset actions (Figures 3.1a and 3.1c), the controller output will stay saturated until the error changes sign. Therefore, the controller will stay inactive until the process measurement crosses over set point. This will result in a considerable overshoot.

One solution is to add the antireset windup relay shown in Figure 3.1aa. This is simply a throttling relay set to operate at 15 PSIG (1 bar), which corresponds to the wide-open position of the control valve. As long as the controller output is below
15 PSIG, the relay transmits the output to the reset feedback connection of the controller and the reset acts normally.

If the output goes above 15 PSIG, the relay begins exhausting the reset feedback line until the output pressure drops to 15 PSIG. Thus it does not affect control except when the system is shut down. At that time it lowers the reset pressure to whatever value it has to be in order to limit its output to 15 PSIG. This allows the proportional action to be active during startup so that it can prevent overshoot. How effective the antireset windup protection is depends upon the quality of the tuning of the controller.

An alternative solution to reset windup on batch applications is to use either a separate derivative unit or a controller with a built-in derivative unit ahead of the proportional-plus-integral sections. This way the derivative unit’s output crosses over the set point sooner than the variable itself does, and this starts the reset to unwind, which is in time to prevent overshoot.

The effectiveness of this circuit also depends upon proper tuning. Too little derivative allows some overshoot; too much causes initial undershoot.

Bibliography


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