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Fundamentals of Closed Loop Control

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Fundamentals of Closed Loop Control

Closed loop control is primarily a concept or philosophy that is independent of the technology required to implement it. An individual can become as deeply involved in the mathematics as desired, but the fundamentals of closed loop control are relatively easy to understand and are essential in the building, operating, or maintaining of any control system. This paper not only discusses these fundamentals but touches briefly on the technology involved.

The Process

The process is the prime component of the system. It is the only reason for the system's existence. Within the context of this paper, a process is broadly defined as the system element, or component that is being controlled. It is that which exists before any hardware is added to measure or control. Many processes operate sufficiently well without the addition of any control equipment. When operated in this manner, the system is called an open loop control system. This will be discussed further in the next section.

In many other practical situations, closed loop control is required to achieve the desired performance from the system. The following is a partial list of typical industrial processes that frequently use closed loop control.

1. Liquid level in a vessel
2. Pressure in a pipe or vessel
3. Flow through a piping system
4. Fluid temperature
5. Nuclear or chemical reaction rate
6. Fluid mixing ratio (concentration)
7. Turbine speed

When studying the overall control system, the process is simply treated as one of the elements in the control loop. A complete description of the process requires a knowledge of such things as the fluid properties and service conditions, vessel or pipeline geometry, chemical or nuclear reaction dynamics, physical dynamics of the device, or any other characteristic that relates changes in the process environment to changes in the process variable of interest.

For the process, as well as all other elements in a control loop, an input and an output can be defined. Definition of the input and output depends upon how the process is used. Input is that which normally influences the status or condition of the process. This is frequently the load disturbance to the process. As a result of this input influence on the process, a parameter of interest would normally be expected to change in some predictable way. The parameter that changes is known as the output. The process output is normally the variable that is to be controlled.

A simple example should help to clarify the process input and output relationship. Assume a flow of gas through a vessel. Further assume that, in this application, the vessel pressure is the object of prime interest. This would be described as a gas pressure process where the *net* flow to the vessel is the input variable and the vessel pressure is the output variable. This relationship is expressed schematically in Figure 1. The loop element, i.e. the process, is represented by a block while the input and output signals are represented by arrows.

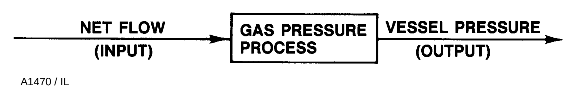

Figure 1. Block Diagram Representation of Process

A knowledge of the process characteristics, such as vessel size and gas properties, are necessary to relate changes in the process input to changes in the process output. These parameters can be used in developing a mathematical transfer function that defines this input-output relationship.

Gain

The process, like every other element in the control loop, receives some kind of input and provides some kind of output as represented by the arrows in Figure 1. The ratio of a change in output magnitude to the change in input magnitude is known as *gain.* The higher the gain, the greater the output change for a given input. Gain simply expresses the sensitivity of an element to changes in its input, and a device with high gain is very sensitive to input changes.

The gain of an element is not a constant quantity, but can change under the influence of certain factors. The mean level of the input signal to the element can frequently have a significant affect on the gain. For example, many processes are such that the gain varies with the load condition. Imagine a gas pressure process with a mean flow rate of 1000 scfh. A 500 scfh

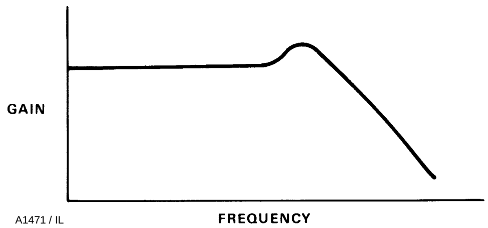

Figure 2. Typical Frequency Response Diagram

increase in the net flow rate would represent a significant change and would undoubtedly cause a large change in the process pressure. Now consider the same process with a mean flow rate of 100,000 scfh. In this case, the same 500 scfh net change in flow rate would cause only a minor change in the process pressure. As the system flow increases, the system pressure becomes less sensitive to the same change in net flow, i.e. the process gain decreases with increasing load flow.

Without resorting to a rigorous mathematical proof, this example gives an intuitive feel for why the gain of a process can vary with the load on the system. Depending upon the type of process, the gain may decrease, increase, or even remain constant with respect to the operating point.

The frequency of the input signal can also have a significant influence upon the gain of the element. This is a phenomenon that is quite familiar to the hi-fi or stereo music buff. Every physical element, just like the stereo amplifier, can respond faithfully to relatively low frequency input signals, but as the frequency increases, a point is reached where the device can no longer keep up with the demands placed on it. Past this point, the gain of the element normally decreases rapidly with increasing frequency. In other words, the device becomes less sensitive to input changes as the frequency increases beyond a certain point. Just prior to this frequency however, the element may experience a type of resonant condition and become even more sensitive to input changes at a particular frequency or band of frequencies.

A graph showing how the gain of an element responds at various frequencies is known as a frequency response diagram or Bode diagram. Actually, a frequency response diagram contains more information than just the gain variation with frequency, but that is all we are interested in at this point. The frequency response diagram for a typical element is shown in Figure 2.

Open Loop Control

The simplest form of process control is known as open loop control, and in simple terms, open loop control means that there is no direct measurement of the controlled variable available for use in making compensating adjustments to the input of the system. This principle is illustrated in Figure 3.

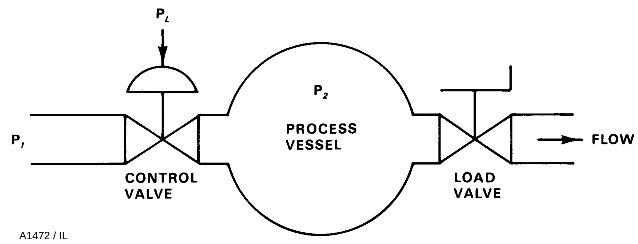

Figure 3. Open Loop Pressure Control

Gas is drawn from the source pressure (P_1) and fed to the process vessel through a valve which is controlled by adjusting the actuator loading pressure (P_L). The purpose of this system is to maintain the vessel pressure (P_2) relatively constant while supplying the downstream load with the gas flow that it requires to operate properly. The downstream load may be anything from a burner to a large distribution network.

If the load flow is known and is constant, it is a simple matter to adjust the loading pressure so that the flow through the control valve will match that through the load valve. If these two flows are exactly matched there will be no variation in the vessel pressure; however, if they are not or if flow through either valve tends to shift slowly with time, there will be a long term drift of P_2.

Indeed, this is one of the inherent disadvantages of open loop control. If the load flow changes in a predictable way, the loading pressure (P_L) can be varied accordingly to compensate for the load change. Unpredictable changes in the load flow will not be compensated for by the control valve and the vessel pressure will fluctuate.

However, there are advantages to open loop control, including low cost, simplicity, reliability, and inherent stability of most processes. Generally, disturbances or changes to an open loop system do not cause it to go into a state of self-sustaining oscillation; however, there are some processes, such as those involving exothermic reactions, that are inherently unstable and require closed loop control to maintain stability.

Block Diagrams

A useful study of control systems would be difficult without the aid of block diagrams. A rather limited view of the block diagram was introduced in Figure 1. A particular element in the system was defined and represented schematically by a block that had one input and one output. The input and output were represented by arrows leading into and out of the block. These arrows are referred to as input and output *signals* since they only represent information about input influences and output responses rather than an actual physical flow of material. The block shown in Figure 1 represents only the process. Referencing this to Figure 3, the process is represented by the pressure vessel and all the connecting piping from the control valve to the load valve.

In Figure 1, notice that the process input is the *net* flow. The net flow consists of two components, the load flow and the control valve flow. These two components are combined with the aid of a summing junction, in Figure 4, to produce the net flow signal.

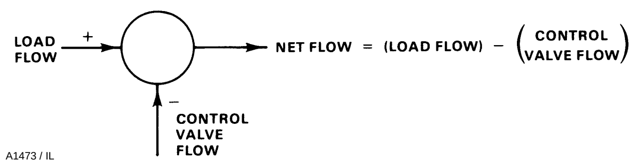

Figure 4. Block Diagram Summing Junction

The summing junction is simply a graphical technique for algebraically combining two or more signals in a block diagram. A summing junction always has only one output signal which is the algebraic sum of all the input signals. Each input has an associated algebraic sign. If no signal is shown, it is normally assumed to be positive.

The valve flow shown in Figure 4 is a result of the actuator positioning the valve to some specific travel position (x). The actuator, in turn, operates under the influence of the loading pressure (P_L). Figure 5 shows how the valve and actuator can be added to the combination of Figure 1 and Figure 4 to produce a block diagram that represents the open loop pressure control system in Figure 3.

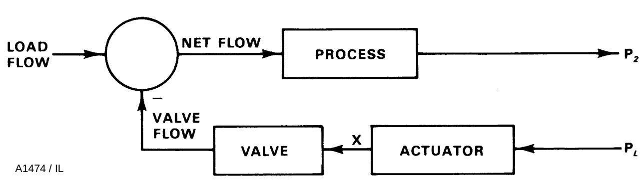

Figure 5. Block Diagram of Figure 3

The block diagram presents a simple, graphical means to keep track of the various elements in the system and their relationship to each other.

Closing the Loop

The simple, open loop control system illustrated in Figures 3 and 5 performs quite satisfactorily in a wide variety of applications; however, it has certain limitations that render it unacceptable in many other situations. Long term drift may be a problem. Frequent load fluctuations can occur, requiring nearly constant attention by an operator to adjust the actuator loading pressure. The operator must intervene to manually close the loop. The quality of control may vary from one operator to the next, or the quality of control may be poorer than desired when an operator is unavailable. All of these factors, among others, led to the technique of letting the control system operate itself, i.e. automatically closing the loop.

Closing the loop means that the system is provided with a way to measure the controlled variable, determine if a deviation from the desired value exists, and automatically provide whatever corrective adjustment is needed for the actuator loading pressure.

One of the simplest forms of closed loop control is the self operated pressure regulator. Self operated means that the energy required to operate the control valve comes from within the system. For the system shown in Figure 3 the process pressure (P_2) can be used to provide the actuator loading pressure (P_L) as indicated in Figure 6. If the control valve allows more flow into the system than the load valve removes, P_2 will rise. This in turn will close the control valve, reducing the amount of flow into the system until it matches the outflow. On the other hand, if the control valve allows too little flow into the system, P_2 will decrease allowing the control valve to open and admit more flow.

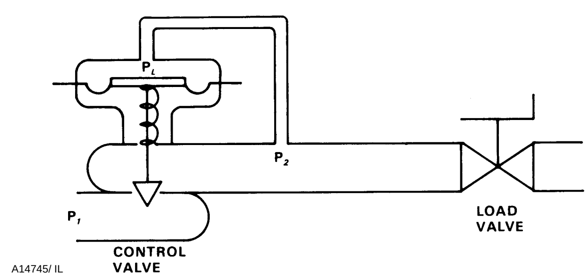

Figure 6. Closed Loop, Self Operated, Gas Pressure Control System

Feedback action from the controlled pressure to the actuator will close the control valve if it is too far open and will open the valve if it is too far closed. This type of compensating action is known as negative feedback, and in a practical sense, simply means that the action of the corrective feedback is always such that it will try to prevent, or reduce, any change in the controlled variable.

In Figure 6, notice that the controlled pressure (P_2) acts against the actuator diaphragm to produce a force that must be balanced by the spring in order to maintain the valve at any flow opening. Because of the spring compression, more pressure is required on the diaphragm when the valve is closed than when the valve is open. This means that as the load flow increases, the control valve must open wider; and the controlled pressure, which acts on the diaphragm, must decrease to allow the valve to open. This decrease in controlled pressure with load flow is called *offset.* In the gas industry, the offset resulting from a no-load to a full-load change is frequently referred to as *droop.*

Since the decrease in P_2 is what opens the control valve to pass the increased flow, this decrease will be proportional to the load flow that exists. This gives rise to the name, *proportional* control. The amount of change that occurs in the measured variable (i.e. P_2 in this case) as the system goes from a low load flow condition to a maximum load flow condition is known as the *proportional band* of the system. In the system of Figure 6, the proportional band is a fixed quantity that depends on the spring stiffness, the diaphragm area, and the valve travel.

In addition to the spring compression which occurs due to valve travel, there is normally some initial compression applied even when the valve is wide open. This initial compression adjustment is normally made by means of a screw thread arrangement on the spring seat. The greater the initial compression applied to the spring, the higher the pressure (P_2) needed to hold the valve in any given position. This does not affect the amount of droop or the proportional band of the system, but it does provide a means for adjusting the range of pressures in which P_2 will operate. By adjusting the initial compression, the controlled pressure can be set to any desired point at any given flow condition. This desired value of the controlled pressure is called the *set point.* In a gas pressure regulation system the set point is normally adjusted at the low load flow. At higher load flows the controlled pressure will droop by some proportional amount.

The block diagram of Figure 5 can be easily modified to represent the closed loop system of Figure 6. The loop is closed by connecting the process pressure (P_2) arrow to the loading pressure (P_L) arrow as indicated in Figure 7.

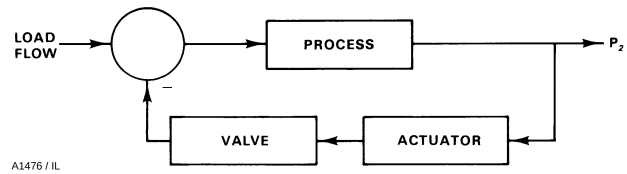

Figure 7. Block Diagram of the Closed Loop System in Figure 6

The process is in the forward path of the control loop, while the valve and actuator comprise the feedback path. The negative sign indicates that the valve flow compensates for changes in load flow to reduce changes in P_2. Considering the closed loop system as a whole, the load flow is the system input and the controlled pressure (P_2) is the system output.

System Stability

Closed loop control overcomes most of the disadvantages of open loop control and provides more accurate and consistent control; however, closed loop control introduces the possibility of loop instability.

The purpose of the control loop in Figure 7 is to maintain the controlled variable at its desired value at all times desired changes in the load. If a deviation of the controlled variable should occur, the system will sense it and provide a corrective feedback action around the loop, i.e. from the controlled variable, through the actuator, valve, and process back again to the controlled variable. Obviously, the more sensitive this control loop is, the greater the correction and the better the performance. This is just another way of saying that high loop gain, or loop sensitivity, is needed for good system performance.

The sensitivity of the loop is determined by the sensitivity of each element in the loop. If the gain of any element is changed, the loop gain changes by the same factor. The total loop gain is determined by multiplying together the gains of all the elements in the loop. Steady-state accuracy, dynamic performance, and a number of other important performance parameters are directly related to loop gain. Provided that loop stability is maintained, all of these performance parameters can be improved with higher loop gain.

If the loop gain is too high, however, the loop will be overly sensitive and will have a tendency to oscillate. As the loop gain increases, the loop will become more oscillatory and disturbances will take longer to die out.

Finally, a loop gain will be reached where the disturbances will never die out and the loop will continually oscillate. This condition is known variously as instability, hunting, buzzing, or oscillation. The control loop, like many other physical systems, has a characteristic frequency at which it oscillates when disturbed. The physical parameters of the system determine this characteristic cycling frequency. In order to maintain loop stability, the gain, or sensitivity, of the loop must be sufficiently low at this critical frequency.

The gain of the various elements in the loop can be related quantitatively to the performance of the system as well as to its stability. Consider the case of two elements in series, as in the feedback path of Figure 7. These series elements can be considered as a single unit by multiplying the series gains together. Figure 8 shows how the actuator and valve can be combined into a single function represented by (H). The elements of the forward path, in this case just the process, can be represented by the function (G).

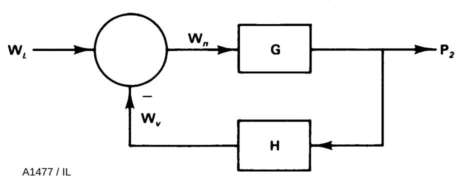

Figure 8. Generalized Version of a Closed Loop, Negative Feedback Control System

Figure 8 can be used to represent any closed loop, negative feedback control system. It can be used to derive a simple mathematical relationship that helps in understanding the system performance. Remembering the definition of a summing junction, a formula can be written to describe its output.

$$W_n = W_L - W_v \qquad (1)$$

Now recall the definition of gain as the ratio of output to input. Utilizing this definition, the output of any element can be written as the product of the input times the gain of the element.

$$W_v = HP_2 \qquad (2)$$

$$P_2 = GW_n \qquad (3)$$

Equation *(2)* can be substituted into Equation *(1)* to eliminate W_v.

$$W_n = W_L - HP_2 \qquad (4)$$

Equation *(4)* can be substituted into Equation *(3)* to eliminate W_n.

$$P_2 = G(W_L - HP_2) \qquad (5)$$

Equation *(5)* can now be rearranged in several algebraic steps to a more useful form.

$$P_2 = GW_L - GHP_2$$

$$P_2 + GHP_2 = GW_L$$

$$P_2(1 + GH) = GW_L$$

$$P_2/W_L = G/(1 + GH) \qquad (6)$$

(*Since (P_2/W_L)* is the ratio of the system output to the system input, Equation (6) represents the gain of the entire closed loop system. Since the sensitivity of the output (P_2) to changes in load (W_L) should be as low as possible, the magnitude of the expression on the right side of Equation (6) should be as small as possible. This is accomplished by keeping the loop gain (GH) as high as possible. If the loop gain (GH) is relatively high, the *one* in the denominator can be safely neglected and Equation (6) reduces to Equation (*7*).

$$P_2/W_L \approx 1/H \qquad (7)$$

Equation (7) illustrates an important principle of closed loop control. When negative feedback is employed around a process, or any other element, and high loop gain is maintained, the response of the total closed loop is essentially independent of the process characteristics (G). If there is any non-linearity or other irregularity in the forward path of the loop, it can effectively be eliminated by the high loop gain and negative feedback.

It should be obvious that high loop gain is the way to achieve good system performance, but as it has already been pointed out, too high a loop gain can lead to loop instability. The loop as it has been defined so far in Figure 7 has no flexibility in terms of gain adjustment to alter the characteristics of the system.

The Controller

The addition of a controller to the loop can greatly improve the quality of control and can provide the flexibility needed to adjust the loop gain to match the requirements of the system.

The controller shown in Figure 9 performs three basic functions. It senses the controlled variable (P_2), compares it to the desired set point value, and provides an output to operate the actuator.

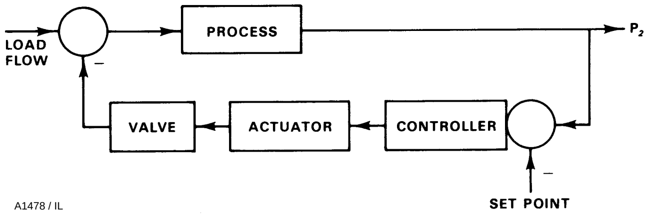

Figure 9. Typical Closed Loop with Controller

The gain of the controller is easily adjustable over some wide range of values. This gain adjustment is sometimes referred to as the proportional band adjustment. Narrowing the proportional band is the same as increasing the gain. A narrower proportional band means that less input to the controller is needed to provide full output, thus the controller is more sensitive to changes in its input signal.

Since the controller is now one of the elements in the loop, changing the gain of the controller will change the loop gain by the same factor. Adjusting the proportional band, or gain, of the controller allows the operator to achieve the best high gain performance consistent with loop stability. Frequently, the operator must compromise and accept poorer control than desired in order to maintain a stable loop.

The simplest type of controller is the proportional controller which has a single gain, or proportional band, adjustment. This controller has only a single mode of operation. If the gain is reduced so that the loop becomes less sensitive at the critical frequency, stability is maintained; but both steady-state accuracy and transient performance suffer due to reduced gain at the high and low frequencies.

Sometimes a two-mode controller, called proportional-plus-reset, is used to improve the steady-state accuracy. By proper tuning of the reset and proportional band controls, the reset action will maintain high gain in the steady-state for improved accuracy, yet the gain will be sufficiently low at the critical frequency to maintain loop stability. Since the gain will also be lowered at higher frequencies, the transient performance will be essentially the same as with the proportional controller.

If the performance specifications are such that the best possible transient control is desired also, a three-mode controller, known as proportional-plus-reset-plus-rate, can be used. Proper tuning of the rate, reset, and proportional band controls can maintain high gain at all frequencies except a narrow band around the critical frequency where the gain is lowered for stability. Figure 10 shows how the frequency response curve would look for an idealized three-mode controller tuned around the critical frequency of the system. A more complete discussion of controller theory and tuning techniques can be found elsewhere.[1]

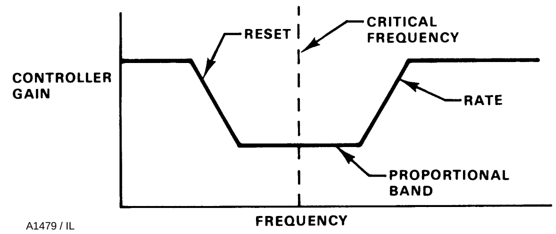

Figure 10. Frequency Response of Three-mode Controller

Indicators, Transmitters, and Sensors

The controller is frequently mounted locally, on or near the valve and actuator; however, the operator may have need to monitor the state of process variable at some remote location. Figure 11 shows how a transmitter can be used to send the process variable signal to any desired remote location.

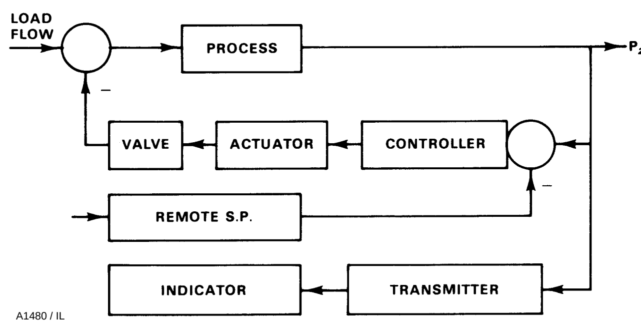

Figure 11. Local Controller with Remote Indication

This is known as a local control system with remote indication. In some systems, a recorder or a recorder-indicator may take the place of the indicator. Since the transmitter and indicator are outside of the closed loop, they do not influence the quality of control or the loop stability; however, the transmitter must be accurate and linear for good quality indication.

Figure 11 also illustrates the possibility of adjusting the set point (S.P.) from a location that is remote from the controller. Again, the remote set point device is outside the control loop and has no influence upon its performance.

It is not always convenient or desirable to have the controller mounted at the valve location. Many industrial plants have the controllers and indicators located in a centralized control room where one

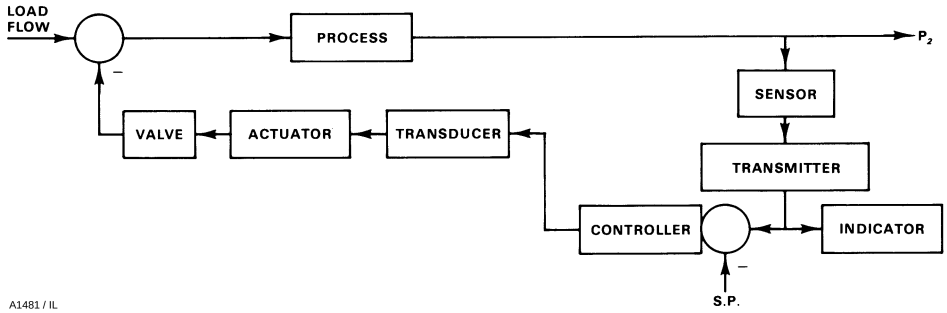

Figure 12. Controller and Indicator Remotely Located in Central Control Room

operator can conveniently monitor the operation of the entire plant. In these instances, a transmitter is necessary to send the process variable signal from the process to the control room.

When the transmitter is used to feed the controller in the control room, as in Figure 12, the transmitter becomes part of the closed loop; consequently, the transmitter's dynamics are very important in addition to its accuracy and linearity. The indicator or recorder, of course, is still outside of the control loop.

Figure 12 shows the sensor as a separate element in the loop. The sensor is the device that actually senses or measures the process variable and converts it into a signal that can be used by the transmitter. A typical example might be a liquid level displacer cage or a differential pressure cell. Many transmitters have sensors that are built in as an integral part of the transmitter, such as the bourdon tube of a pressure transmitter. If the sensor is a separate element, it will have separate dynamic characteristics which must be accounted for in the loop.

Figure 12 also shows the inclusion of a transducer in the loop between the controller and the actuator. One function of the transducer is to change from one type of signal to another, e.g. a transducer may be used to convert an electronic signal from the controller into a pneumatic signal to operate the actuator. Since the transducer is contained in the loop, its dynamic characteristics must be considered in any study of the system.

The transducer also frequently serves the function of a booster. In this capacity it operates as a power amplifier between the controller and the actuator. The controller is not usually a high power output device and when it is forced to drive a large actuator it may be seriously loaded down to the point where the controller response suffers drastically. When the booster-transducer is used, the large actuator load is removed from the controller thus making the controller functions more effective.

Positioners and Boosters

While the transducer is used primarily as a means to convert from an electronic signal to a pneumatic signal it secondarily acts as a power amplifier that isolates the actuator load from the controller. In an all pneumatic system there is frequently a need to provide the same type of dynamic isolation between the actuator and the controller. This can be provided by either a positioner or a booster. A knowledge of the loop dynamics is necessary to decide which, if either, of these two devices should be used for a given application. The positioner is really a servo mechanism that accepts a signal from the controller and drives the actuator stem to whatever position is specified by the signal from the controller. The positioner measures the actual stem position and provides negative feedback around the actuator to obtain accurate positioning.

Positioners have been around the process control industry for many years and many rules-of-thumb about their application have proliferated. The majority of these rules-of-thumb stem from an intuitive fear of sticking valve stems, valve unbalance, and friction. The chief characteristic of these rules-of-thumb is their poor reliability. Frequently, the performance of a control loop may be improved by either adding or removing a positioner in contradiction to the old rules of thumb.

In 1969, the results of a research program were published which related the proper application of positioners to the dynamics of the process control loop.[2] In this study, process control loops are divided into the categories of fast and slow. These categories are defined by the relationship of the frequency at which the complete control loop tends to cycle to the individual frequency response of the positioner-actuator combination.

This study concluded that the use of positioners is clearly beneficial on relatively slow systems and clearly detrimental on relatively fast systems. Moreover, the need for using or not using a positioner would seem to be completely independent of the old rules-of-thumb, with perhaps the following exception. If the stem friction is unusually high, it becomes increasingly important to ignore the old rules and follow the fast-system/slow-system principle for positioner application.

It should be realized that a simple spring and diaphragm actuator, if properly sized, will often do an excellent job without the aid of auxiliaries such as either a positioner or a booster amplifier.

Three cases are recognized, however, where one of the two auxiliary devices should be considered. They are:

1. Where the loading pressure to the actuator must be increased above the standard 3-15 psi range to obtain adequate thrust or stiffness.

2. Where split-range signals are required.

3. Where the best possible control is desired; i.e., the minimum overshoot and fastest recovery of the system is wanted, following a disturbance or load change.

The cases cited above only indicate that a positioner or a pneumatic booster amplifier should be considered, the choice of which should be used depends on the system dynamics.

If the system is relatively fast, such as is typical of liquid pressure, most flow, and some gas pressure control loops, the proper auxiliary choice is a pneumatic booster amplifier.

If the system is relatively slow, such as is typical of liquid level, blending, temperature, and some reactor control loops, the proper auxiliary choice is a positioner.

Fortunately, those systems where it is most difficult to determine whether the system is fast or slow, relative to the positioner-actuator, are most likely to fall in the transition region between clear-cut cases. In this situation, the importance of observing the guidelines is minimal. There are also many systems where adequate control is either quite easy, or stringent requirements do not exist. In these cases, relatively loose controller settings are acceptable and the misapplication of a positioner, though uneconomical, may give quite tolerable performance.

In the case of springless actuators, such as a double-acting or push-pull piston, the use of a positioner is unavoidable. For slow systems, where a positioner is normally beneficial, the choice between springless and spring type actuators may simply be an economic one. For fast systems, where positioners should be avoided, a spring biased actuator without a positioner should be used if possible. If the thrust requirements necessitate a springless actuator, there is no alternative but to use one and accept the required looser controller settings. As mentioned this will not always present a serious penalty.

Actuators

The purpose of the actuator is to provide the force or thrust needed to operate the valve through the range of the valve travel. Actuators are divided into the two basic categories of diaphragm actuators and piston actuators. The diaphragm actuators are economical and utilitarian while the piston actuators combined with higher operating pressures are used for the high thrust applications and may offer economic advantages even with the inclusion of a positioner. The size of the actuator and the operating pressure range determine the available thrust.

Besides thrust, other important actuator characteristics are accuracy, load sensitivity, dynamic stiffness, stroking speed, and input impedance. The no-load inaccuracy of a standard diaphragm actuator can be expected to be about one to five percent of the span while the addition of a positioner can improve this to one percent or less.

Load sensitivity is the steady-state change in stem position caused by a given load change. It is usually expressed as the error or stem movement in percent of rated travel in response to a load change of 100 percent of the rated load. Rated load is defined as the force produced by the actuator when the diaphragm pressure varies through its normal range. If a force of this magnitude is applied externally to the actuator, a change in stem position will occur. This change in stem position, expressed as a percent of rated travel, is defined as load sensitivity. By definition, the load sensitivity of a standard diaphragm actuator will always be 100 percent. The addition of a positioner to the actuator can reduce the load sensitivity to one percent or less.

The stiffness of the actuator is closely related to the load sensitivity and positioner dynamics. Under steady-state conditions the stiffness is the reciprocal of load sensitivity. Stiffness is defined as the ratio of a change in load force to the change in stem position it causes. High dynamic stiffness is desirable in an actuator to reduce the effect of buffeting due to fluid turbulence. Actuator stiffness is dynamic in nature since it varies with time and frequency. Figure 13 shows how the dynamic stiffness varies as a function of frequency.

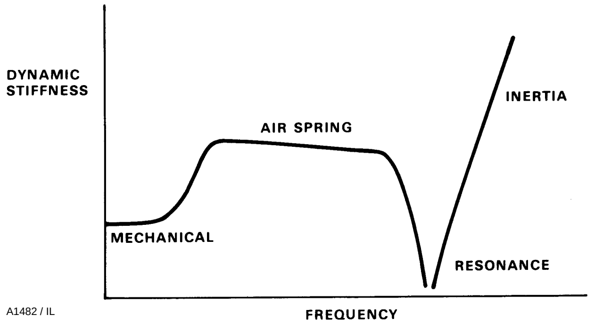

Figure 13. Dynamic Stiffness of a Standard Diaphragm Actuator

At very low frequencies the dynamic stiffness is equal to the mechanical stiffness of the actuator spring. As the frequency increases, the actuator springmass element picks up some viscous damping from the pumping flow of air into and out of the actuator diaphragm casing. This damping action produces an air spring effect that increases the stiffness of the actuator at these frequencies. At still higher frequencies, the actuator approaches its resonant frequency and the stiffness becomes very low. At frequencies above this resonant frequency the stiffness begins to increase because of inertia.

It is interesting to note in Figure 14 that the addition of a positioner to the actuator can increase the dynamic stiffness at low frequencies, but at higher frequencies the dynamic stiffness approaches that of a simple diaphragm actuator.

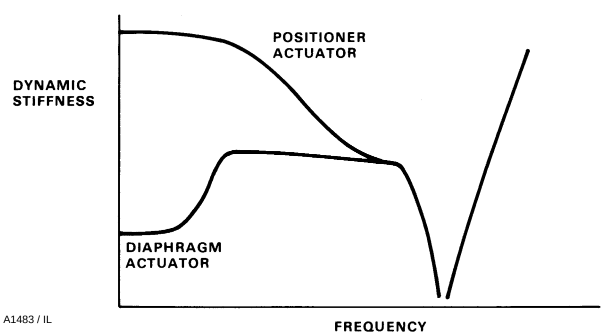

Figure 14. Dynamic Stiffness Comparison of a Positioner-Actuator and a Simple Diaphragm Actuator

If the dynamic stiffness of an actuator or a positioner-actuator is too low, thus allowing the actuator stem to respond to buffeting forces, a hydraulic snubber can be added to the actuator to provide greater stiffness through increased damping. While friction is normally undesirable, it may be helpful in reducing the actuator response to buffeting forces.

The actuator stroking speed is defined as the full actuator stroke divided by the time necessary for the actuator to fully stroke after the driving power amplifier output is switched from zero percent to 100 percent output level. This stroking speed depends on the maximum output power of the device driving the actuator, as well as the size of the actuator, load forces, and inertia. The stroking speed is affected not only by the volume of the diaphragm casing, but also by the elasticity of that volume. The apparent volume of a typical diaphragm actuator can be as great as 40 times the measured physical volume of the actuator casing.

The input impedance of an actuator or positioner-actuator is an important characteristic because it can affect the transient response of a control system by the loading effect it imposes on the driving instrument. Pneumatic actuators have a capacitive type of input impedance which is due to the actual volume and the elastic volume of the diaphragm actuator casing. Often a positioner or impedance matching amplifier (booster) will be used with an actuator for the specific purpose of decreasing the loading effect on the driving instrument.

Valves

The function of a control valve is to modulate the flow of a process fluid in accordance with some external signal, usually generated by the controller. The important performance characteristics, from the standpoint of control, are determined by the relationships between flow, pressure, and valve travel. Other practical application considerations are valve body pressure ratings, shutoff requirements, material selection, valve style, valve size, recovery characteristics, and valve characterization.

Finding the appropriate combination of all these valve parameters for a given application is not particularly difficult, but it does require careful attention to a number of details.[3]

Once the physical features of the valve have been selected, it is imperative that the correct size valve is selected for the fluid conditions that will actually exist in service. Undersizing the valve will unnecessarily restrict the flow and starve the process. Oversizing the valve is unnecessarily expensive and can lead to loop instability or poor performance due to excessive valve gain which must be compensated for in the controller.

The capacity of a valve is a function of the flow area, pressure differential, valve style, and pressure recovery characteristics. A great deal of literature exists which discusses the proper application of fluid theory to the problem of valve sizing.[4,5,6,7,8,9,10] Practical procedures for calculating required valve sizes are available from various control valve manufacturers. Mathematical formulas, slide rules, charts, and nomographs are available for determining liquid, gas, and steam sizing coefficients required for any given application.

One important consideration is valve characterization. Valve characterization is normally accomplished by shaping the valve trim parts so that a particular flow relationship to travel is achieved. This establishes a particular variation of the valve gain with load flow. The gain of many processes will vary with load. This gain variation can cause the loop performance to suffer in a variety of ways, even to the point of system instability. To maintain uniform system performance, the process gain variation must be compensated for elsewhere in the loop. The control valve is the most practical place to achieve this compensation.

With constant pressure drop across a characterized valve, there is an inherent relationship between flow and valve travel that is designed into the valve. This inherent flow characteristic establishes the gain variation of the valve with load. When the valve is installed in a system where the pressure drop can vary, a different flow characteristic is obtained from the valve. This is called the installed flow characteristic. The study of valve characterization can become quite complex, but a knowledge of the basics will greatly assist the individual in the selection of the proper characteristic for a given application.[11]

Conclusion

Although some systems will operate satisfactorily in an open loop configuration, closed loop, negative feedback control offers many performance advantages. Closed loop control also introduces the possibility of loop instability which does not exist with open loop control.

A knowledge of each of the elements that comprise the control loop is necessary in order to build, use, and maintain the system so that the best performance can be achieved. The block diagram is an important tool in analyzing how each of the elements in the system affect the loop performance.

Loop stability, as well as the performance characteristics of the system, depend heavily upon the loop gain. High loop gain gives good transient and steady state control, but it also leads to loop instability. The function of the controller is to provide a means for adjusting the gain of the loop to fit the system dynamics.

This paper has dealt with some of the fundamentals of closed loop control. An understanding of these basic principles can greatly assist the individual in building, operating, or trouble shooting any control system.

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