technical monograph 29

Fundamentals of Flow Characterization

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Introduction

Achieving optimal control system performance keys on selecting or specifying the proper flow characteristic. Therefore, people who design, operate, or maintain process controls components and systems need to understand the fundamentals of flow characterization. Characterization is the establishment of a relationship between the output and input of any device. In particular, the relationship between valve flow and valve travel is called the valve flow characteristic. Understanding the link between good control performance and flow characteristics requires some knowledge of closed loop control.

Closed Loop Control

The purpose of process control is to maintain certain process parameters such as pressure, flow, temperature, liquid level, etc. at their desired values at all times despite changes in the process load. Load change usually, but not always, means a change in process throughput. Any change in the system, which requires a change in control valve percentage of opening, should be considered a load change.

Typically, closed loop control is employed in these systems. There are many types of control loops, but all simple loops are specific cases of the generalized control loop in figure 1. Obviously all loops contain the *process* to be controlled. Many factors determine the behavior of specific processes, such as containment vessel geometry, fluid properties, chemical reactions, heat transfer, and more. Although intricate details may affect the process behavior, the control engineer does not need to know about them as long as the qualitative relationship between load and controlled variable is known.

The controlled variable may be measured by a *transmitter* and its value expressed as a signal to the *controller.* The measuring device is not always a separate piece of hardware. For example, a pressure controller often contains its own sensor. A regulator combines the sensor with other functions. The signal corresponding to the process variable is compared by the controller to the desired or *set point* value. The controller makes appropriate changes in its output to eliminate the difference between actual process variable value and the set point.

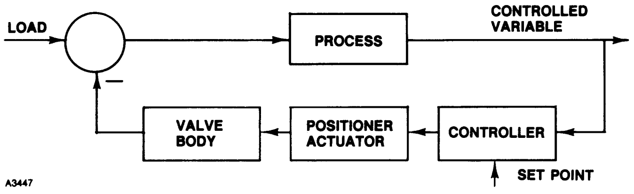

Figure 1. Block Diagram of a Generalized Control Loop

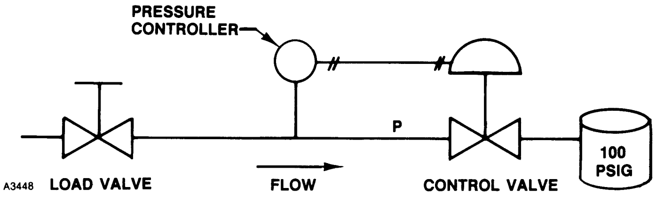

Figure 2. Liquid Pressure Control Loop

The controller output goes to the block labeled *positioner/actuator*. This device may be an actuator only or it may be an actuator in conjunction with a booster or a positioner. The overall dynamic characteristics of these components are interdependent, so they are considered as one unit.

The last device in the control loop is the *control valve body*, also known as the final control element. The actuator adjusts the travel of the valve body's restricting component according to the controller output. Travel may be linear or rotary.

Gain

Every element in the control loop receives an input and provides an output. Each element has a certain relationship between output and input known as its characteristic. As was mentioned in the introduction, the valve characteristic was between flow and travel. The ratio of a change in output to a change in input is know as *gain*. The higher the gain, the greater the output change for a given input change. Gain can also be thought of as the slope of the characteristic curve.

Gain is not necessarily a constant. Process gain often varies with load. The following is a simple example of how this occurs. Consider a water pressure control loop as shown in figure 2. The flow in through the load valve equals the flow out through the control valve. Assume the control valve exhausts to a constant pressure of 100 psig, P is 200 psig, and the mean flow is 100 gpm. By using the sizing equation from reference 1, we can infer that the control valve's current flow coefficient is 10. If the load increases to 200 gpm without any corrective action taken by the controller, the process variable P would increase to 500 psig:

$$P_1 = P_2 + G\left(\frac{Q}{C_v}\right)^2 \tag{1}$$

$$P = 100 + 1\left(\frac{200}{10}\right)^2 = 500\,psig \tag{2}$$

The average process gain would be 3:

$$Gain = \frac{\Delta_{output}}{\Delta_{input}} = \frac{500 - 200}{200 - 100} = 3 \tag{3}$$

If the load increases again by the same amount to 300 gpm, P would be 1000 psig and the average gain would be 5:

$$P = 100 + 1\left(\frac{300}{10}\right)^2 = 100\,psig \tag{4}$$

$$Gain = \frac{1000 - 500}{300 - 200} = 5 \tag{5}$$

Input changes do not have to be considered as discrete. Input values may vary continuously as in a sinusoid. Gain is then the ratio of output to input amplitudes. Gain is normally a function of frequency. Process and control component gains often attenuate, or become less, at sufficiently high frequencies. In such cases the device is considered unable to keep up with rapid input changes. Gain at zero frequency is known as static gain.

The output may also be out of phase with the input. An output, which is behind the input in time is said to lag. Phase lag is measured as an angle, with 360 degrees equal to one cycle. Phase angles are also a function of frequency.

The product of the gains of all the elements in the loop is known as *loop gain*. The loop gain determines the performance of the control loop. The phase angles of all elements are summed to find the overall phase relation.

Performance

The criteria for good control loop performance vary, but include: stability, low steady-state error, fast response to correct process upsets, and a single controller setting for all process load levels. The loop gain directly affects all of these.

Stability requires that the loop gain be less than unity at the frequency where the loop phase lag is 180 degrees. This frequency is known as the loop cycling or critical frequency. Good steady-state accuracy requires high static gain. Fast response is enhanced by high gain at other frequencies. Simply put, good performance means a gain as high as possible without causing instability. Most controllers have gain adjustments to achieve this optimal loop gain.

The problem is that loop gain changes every time process gain changes. Because process gain often changes with load, the controller must be retuned to attain optimal loop gain after each load change, unless the gain of another loop element changes to counteract the process gain change. Then the final criterion of good performance listed above would be fulfilled.

Compensation

The purpose of flow characterization is to compensate for process gain changes so that loop gain remains independent of load. A very simple way to accomplish this is to make all the control devices *linear* except the valve body. (Linear means that output is directly proportional to input and hence gain is constant.) This allows the same transmitters, controllers, and actuator/positioners to be used for a variety of processes. Only the valve body gain needs to be tailored to achieve compensation. Historically, this method was the easiest way to effectively characterize flow. Although other means exist, this is still the most common.

Globe valve body gain is manipulated by shaping trim parts appropriately. Globe valve bodies are available with a selection of trim to attain various flow characteristics. Normally, a standard trim is selected which most nearly compensates for other gain variations in the loop. Occasionally, special custom characteristics are justified for critical control applications.

Actuators could be designed with a selection of characteristics, but their simplicity and economy would be lost. Spring and diaphragm actuators are naturally linear devices if valve stem flow forces are ignored. Pneumatic piston, hydraulic, and electromechanical actuators have their characteristics determined by their positioners. Positioner and controller characterization will be discussed later.

Transmitters are normally available with only one characteristic. Usually that characteristic is linear, but the output signal of a differential pressure flow transmitter is proportional to the flow squared. The corresponding gain changes must be compensated for similar to process gain changes. Sometimes the transmitter signal is processed by a square root extractor; other times the net effect of all sources of gain variability are compensated for together.

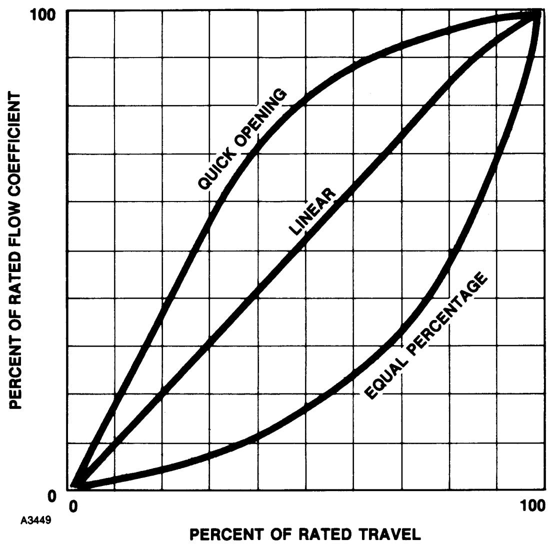

Figure 3. Inherent Valve Flow Characteristics

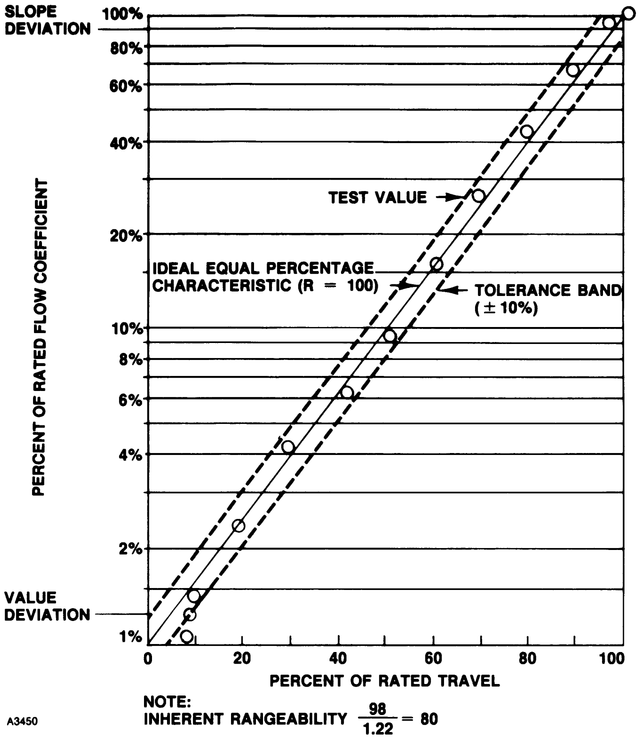

Figure 4. Ideal versus Real Characteristic

Valve Characterization

An *inherent valve flow characteristic* is defined as the relationship between valve travel and flow rate through a valve body, under constant pressure drop conditions. The inherent characteristic can also be defined as the relationship between flow coefficient and travel. The three common valve characteristics are linear, quick opening, and equal percentage. They are shown graphically in figure 3.

The linear characteristic forms, as its name implies, a straight-line plot of flow coefficient versus travel. Straight lines have constant slope, therefore the linear gain is independent of travel. This characteristic is the mathematically ideal one for liquid level and certain flow control applications requiring constant gain.

The quick opening characteristic originated as the natural byproduct of the simple valve trim geometry often found in regulators and relief valves. As the name suggests, this type of valve body opens quickly to establish significant flow with minimum travel. The flow coefficient curve is approximately a straight line with slope about 1.5 times that of a linear characteristic for the first 70% of flow capacity. It then decreases asymptotically to full flow capacity. Therefore, the gain of the quick opening characteristic is constant up to 70% of the rated flow coefficient and then decreases.

The third characteristic is equal percentage, because equal changes in travel produce equal percentage changes in the existing flow coefficient. In other words, the slope of the curve is proportional to the flow coefficient. Therefore, inherent valve body gain is directly proportional to flow. The equal percentage characteristic can be expressed mathematically by:

$$C_v = C_{vm} R^{\left(\frac{y}{y_m}-1\right)} \qquad (6)$$

where:
C_v = flow coefficient
C_{vm} = rated flow coefficent
y = travel
y_m = rated trave;
R = rangeability (a constant for a particular valve body)

This equation plots as a straight line with slope R on semi-log axes as shown in figure 4. Note that the ideal flow coefficient is non-zero at zero travel. Real equal percentage valve bodies can attain shutoff, so actual characteristics deviate from the ideal at small travels as shown in the figure.

The equal percentage characteristic is mathematically elegant and also a natural result of the trim geometry of butterfly valve bodies. Sometimes a natural characteristic is labeled as approximately linear or approximately equal percentage if major deviation from the ideal occurs throughout the travel. Other characteristics, with labels such as modified parabolic or modified equal percentage, result from specific valve trim designs and generally fall between linear and equal percentage.

Rangeability

The term rangeability used in the mathematical definition of the equal percentage characteristic has another usage. The *inherent rangeability* of a control valve is defined as the ratio of maximum to minimum flow coefficient within which the deviation from the specified inherent flow characteristic does not exceed some stated limit. In this sense, rangeability applies to all rigorously defined characteristics, not to just the equal percentage characteristic. Unfortunately, one person uses the term *inherent rangeability* to apply to all characteristics while another uses the same term to apply only to the equal percentage characteristic.

Typical values of inherent rangeability run from 20 to 300 depending on valve body style. These values also depend on the allowable deviation criteria used. If we use a tolerance band of 10% on capacity and a factor of two on slope, the real equal percentage characteristic of figure 4 has a rangeability of 80. High rangeability is a desirable feature. It implies a greater range of flows over which proper compensation occurs. Other factors like bi-stable flow, friction, and changing pressure condition also contribute to flow range limitations. The ratio of maximum to minimum *flow* over which the valve body provides satisfactory control is called *installed rangeability*.

Installed Valve Characteristics

Pressure conditions also affect valve flow characteristics. Flow rate through a valve body is a function of pressures and flow coefficient. If pressure conditions change with travel, the relation of flow (output) and travel (input) gets altered. The variation of pressures with travel is process or installation dependent. The flow versus travel relationship under a specific set of conditions is called the *installed flow characteristic.*

If pressure conditions are held constant, the installed flow characteristic has the same shape as the inherent flow characteristic. Consider a linear valve body flowing an unchoked incompressible fluid at several different pressure drops. For each drop the relation of flow and travel is linear as shown in figure 5. However, the slope or gain is less at lower pressure drops.

Assume this valve body is installed in a process where the valve ΔP decreases with load. Figure 6 shows a hypothetical locus of points defining the flow rate as a function of travel. The points are found by selecting the appropriate ΔP curve for each increment of travel. Note that this installed flow characteristic curve is not linear.

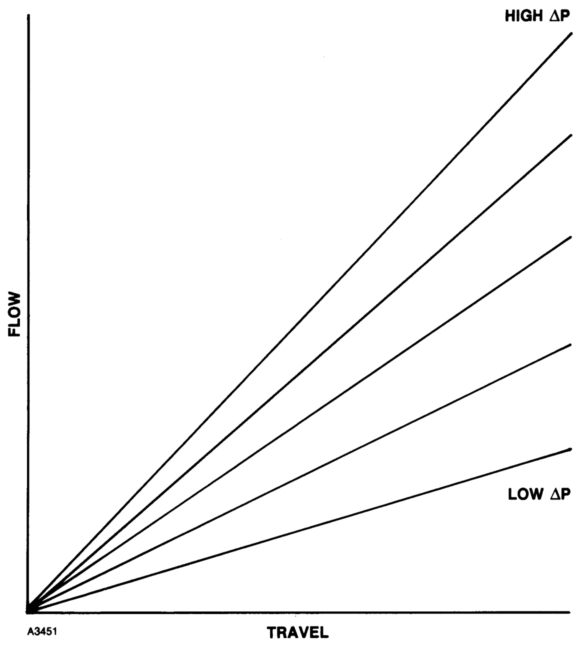

Figure 5. Valve Body Gain Variation with ΔP

Control valve gain is therefore a function of inherent gain and the process influence. Proper compensation is achieved by selecting a valve body with an *installed* characteristic that offsets process gain changes. This requires knowing what the valve body ΔP is at all loads for the process. Our graphical example was for incompressible flow where flow depends on a ΔP.

We can generalize to any influence like the inlet pressure dependence of choked compressible flow. Our discussion of inherent characteristics did not distinguish between incompressible and compressible flow coefficients. In globe valve bodies, the ratio of these coefficients is nearly constant throughout travel and both characteristics are the same. High recovery ball and butterfly valve bodies normally have a fluctuation in the coefficient ratio and hence have slightly different inherent characteristics for choked, compressible, and incompressible coefficients (figure 7). The characteristic for subcritical compressible flow falls between the two extremes shown. Its location is determined by the magnitude of compressibility effects.

Positioner Characterization

Actuators with positioners can be characterized. This is valuable when a valve body is only available with one characteristic, as is typical of rotary valve bodies.

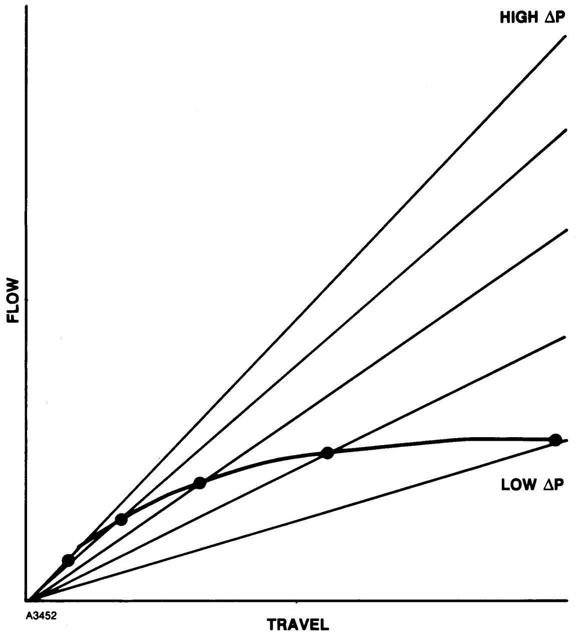

Figure 6. Installed Flow Characteristic For Linear Valve Body With Decreasing ΔP

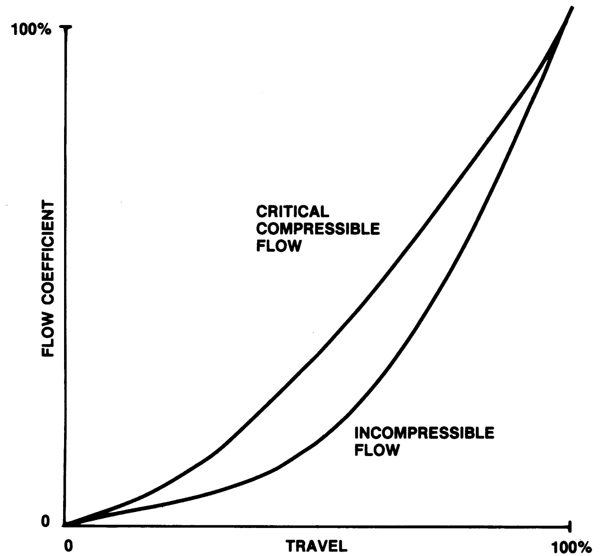

Figure 7. Effect of Compressibility on Inherent Flow Characteristic of a High-Recovery Valve Body

An actuator/positioner is a closed loop control system with travel as the controlled variable. The input signal from the controller establishes the set point. Various characteristics are obtained by adjusting the feedback with cams. Figure 8 shows a standard set of actuator/positioner characteristics. The position feedback serves to cover up actuator hysteresis due to friction and the nonlinear transfer function of linear to rotary motion.

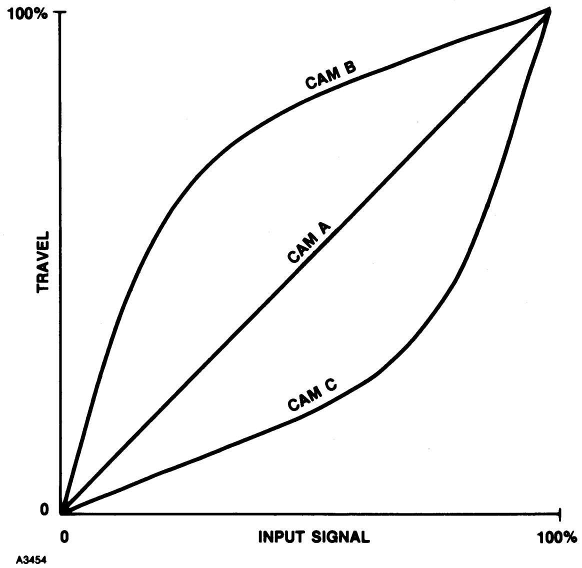

Figure 8. Positioner Characteristics

This loop within a loop, or *cascade* loop, has an additional requirement for good performance. The inner loop must have a critical frequency which is much higher than that of the outer loop. Therefore, positioners should not be used on "fast" loops (reference 2). This usually eliminates positioner characterization as a method of compensation for flow and liquid pressure control.

Another problem, which confounds characterization, is that gain changes with load can be frequency dependent. Figure 9 shows an idealized set of pressure process gain curves. The frequency at which gain begins to attenuate (*break frequency*) shifts with static gain changes such that high frequency gain is load independent. The proper characteristic for this process depends on which gain region contains the critical frequency. This consideration is important no matter which control element is doing the compensating.

Positioners with characterization in the feedback path can demonstrate similar shifts in break frequency. If the desired characteristic has large gain changes, it may be difficult to keep the inner loop break frequency sufficiently high--even on slow processes. If positioners were characterized in the forward path, this complication would be eliminated. In general, positioner characterization requires extra scrutiny to ensure that it is effective.

Controller Characterization

Traditionally, controllers have been designed as linear devices such that output change is proportional to the deviation from set point. Compared to other

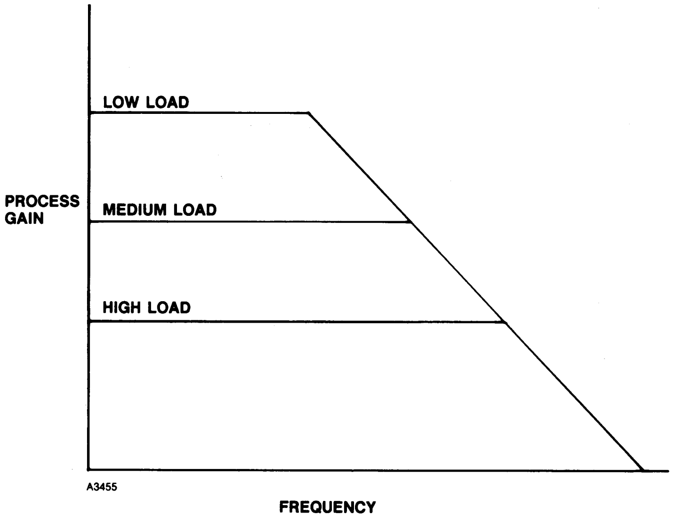

Figure 9. Pressure Process Gain Curves

characteristics, a linear device is often a simpler design with pneumatic and analog electronic equipment.

The need for perfect compensation has decreased as controllers have become more sophisticated. *Reset action* on controllers has boosted gain at low frequencies thus minimizing steady-state error without raising the gain at the cycling frequency. *Rate action* in combination with reset provides for good transient response without destabilizing. These controllers can be *detuned* by lowering the gain of the proportional action such that there is a gain margin at the critical frequency. Then, a small residual variation in loop gain after compensation does not cause instability. These three-mode controllers have not eliminated the need for valve body characterization. Good performance cannot be expected from loops that are excessively detuned to handle large swings in gain.

The advent of microprocessor-based distributed control systems has finally provided an effective method of compensation other than valve body characterization. Programmable controllers can theoretically implement any input to output relation. A special characteristic can be tailor made. This characteristic can be improved upon without a process shutdown by updating the program as more is learned about the process. Process gain does not have to be inferred from a single variable (load), but rather can be calculated from many observations. The dynamic limitations of electronic controller characterization are not nearly as significant as those of positioner characterization. Excessive valve stem or shaft friction may degrade performance more if controller characterization is used. But in general, digital control allows effective compensation with a valve body that has only one available characteristic.

Even with digital control, the installed valve characteristic must be known so the proper algorithm can be written. Inherent rangeability is also still relevant because it tells us the range of flows over which the algorithm is valid. Digitally controlled loops are a small minority of all loops, but they are growing rapidly. Some loops will never be converted because of cost, complexity, etc. Hence, controller characterization will never replace valve body characterization completely, but it is an effective alternative.

Summary

Good performance of closed loop process control systems requires the loop gain to remain constant with respect to load. Process gain changes must be compensated for by properly selecting control components. Valve bodies are practical devices to characterized. Valve body gain is a function of the inherent characteristic and pressure conditions. Positioners can be characterized, but this is effective only under certain circumstances. When the controller is a programmable electronic device, compensation can be easily attained with it.

References

1. **Fundamentals of Valve Sizing for Liquids**, TM-30, Marc L. Riveland, Fisher Controls International

2. **Guidelines for the Application of Valve Positioners**, TM-23, Sheldon G. Lloyd, Fisher Controls Company, 1969

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