# Characterizers for control loops

*By F.G. Shinkskey*

## Introduction

Commercial controllers such as the PID series (proportional, integral, derivative, and their combinations) are linear devices within their normal operating range, i.e., within set limits of input and output signals. Yet most fluid processes which they are assigned to control are nonlinear to some degree, which means that their gain in response to control action is subject to change. In this case the controller cannot be optimally tuned except at one specific operating condition. When the process load or controller set point change, the tuning parameters may no longer provide the optimum recovery from disturbances. In some cases, the process gain can even vary with the magnitude of the disturbance or the deviation of the controlled variable from set point.

If the variation in process gain is less than about 50 percent over the full operating range, the response penalty will not be severe. However, the controller should be tuned at the operating point where the gain is highest, so that the loop will be stable at all times. For some loops, the gain variation is much greater than this, in which case the controller gain is much lower than optimum at normal production conditions, substantially compromising its performance. Two examples are given here where the gain variation was sufficient to cause control problems, and was corrected by applying characterization.

## Locating the Nonlinearity

Most nonlinear behavior is associated with the final element—the control valve. Its characteristic is often incorrectly chosen. But when the pressure drop across the valve is variable—which is commonly the case—none of the standard valve characteristics will deliver flow linearly with controller output. Furthermore, some processes such as liquid-liquid heat exchangers do not transfer heat in a linear relationship with fluid flow, in which case temperature is not linear with flow.

When the process nonlinearity is related to flow or process load, the loop gain will be different for each value of load, and therefore with each value of controller output. This is manifested as variable damping as a function of controller output. The loop could be lightly damped at high values of controller output, or at low values, depending on the shape of the nonlinear relationship. Quite often, the highest process gain occurs at startup or standby conditions, requiring the controller to be tuned there for stability; then it will not be sufficiently responsive at normal production conditions.

It is also possible for the nonlinear behavior to be associated with the controlled variable, but this is far less common. The two applications most frequently encountered are flow and pH loops. Nonlinear flow measurements are those where head or differential pressure across a restriction is transmitted to the controller. Modern dp transmitters and digital controllers can extract the square root of the measured head, linearizing the flow signal for orifices and nozzles; similar calculations can be made to linearize flow signals from flumes and weirs.

With pH measurements, however, the problem is more complex. The relationship between reagent delivery and pH is logarithmic, capable of producing a gain variation over several orders of magnitude. And it is not a simple relationship—the shape of a curve is a function of the ionic species in solution and their concentrations. Each process may have its own characteristic curve, and even a family of curves, changing with time. Measurement of oxidation-reduction potential and ionic species other than hydrogen follow similar relationships.

If the variable process gain is associated with the controller output, then a curve characterizer applied to the controller output signal can correct the problem, by essentially modifying the valve characteristic. For the head flowmeters described above, characterization was applied to the flow measurement. Similarly, for pH loops, characterization needs to be applied to the measurement (and to the set point).

## pH Control

A typical titration curve for industrial wastewater is shown in Fig. 1. The curve is produced by titrating a sample with caustic in a laboratory, or by incrementally raising the dosage

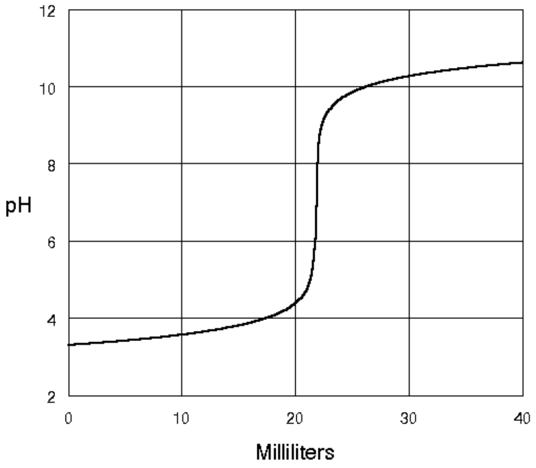

Fig. 1. Titration curve for typical wastewater.

## Titration curve for typical wastewater

of caustic delivered to the plant neutralization vessel under constant load (a far slower and less-reliable procedure). The set point for the pH controller is usually positioned in the region of neutrality, where the curve has its steepest slope—for this curve, the maximum slope is 75 for a pH range of 2-12. Consequently, the controller gain must be adjusted for stability there, to avoid limit-cycling, a constant-amplitude cycling which can substantially increase reagent consumption.

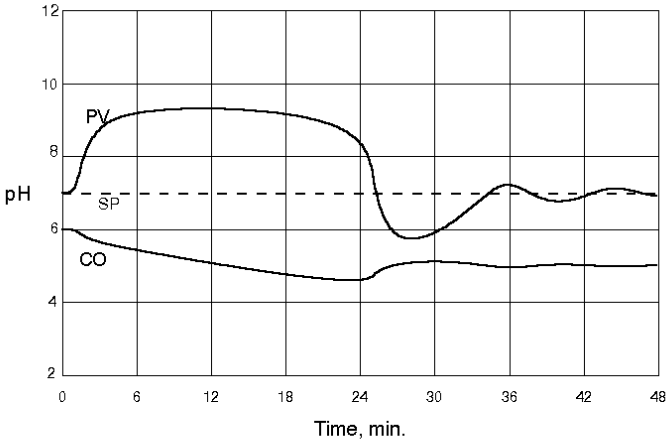

Fig.2. Step load response without a characterizer.

## Step load response without a characterizer

Figure 2 describes the simulated response of a pH control loop based on the titration curve of Fig. 1 (without nonlinear compensation), following a step decrease in acid load to the neutralization vessel. The vessel is simulated as being well-mixed, and having a residence time of 20 minutes. The set point (SP) is positioned at pH 7. Although the PI controller is tuned for light damping at set point, as observed toward the end of the response, recovery of the process variable (PV) from the upset is very slow, and is followed by a large overshoot. Note that the controller output (CO) moves very slowly toward its new steady state, because the controller gain is very low (0.167). For smaller load changes, the response will be better, and for larger upsets, it will be worse.

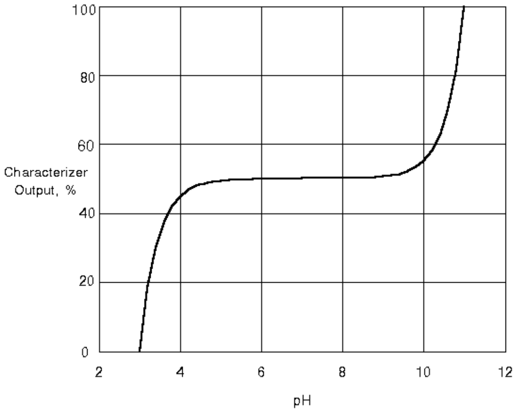

Fig.3. The characterizer is the pH curve rotated.

## The characterizer is the pH curve rotated

The loop can be linearized by placing a complementary nonlinear function in the path of the pH measurement and set point—that function is shown in Fig. 3. In essence, this characterizer converts pH values into equivalent concentration of caustic in solution, linear with the delivery of caustic by the controller.

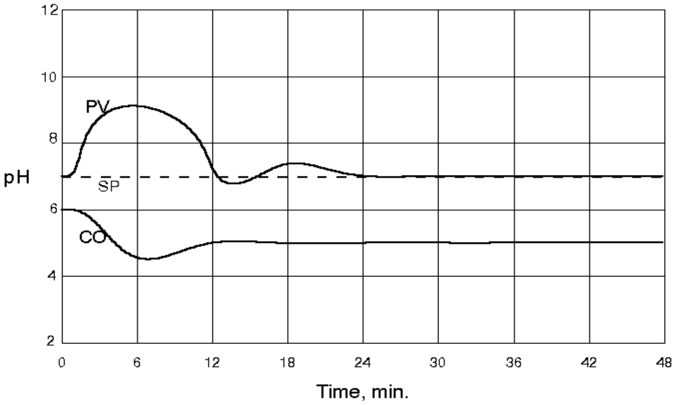

Fig.4. Step load response with a matched characterizer.

## Step load response with a matched characterizer

Figure 4 repeats the step change in acid load with the characterizer applied to the controller. The recovery is much quicker and damping uniform—observe that the trajectory of the controller output is representative of a linear loop. The integrated error between PV and SP has been reduced by a factor of two and the integrated absolute error by almost a factor of three by the addition of the characterizer. The controller gain has been increased to 7.7, but the loop is now more heavily damped than before, and settles much more quickly.

Many other possible curves exist—some asymmetrical , as well as the possibility that the set point may be positioned somewhere other than in the center of the curve. For best results, the characterizer should match the titration curve as accurately as possible. This requires at least ten points on an X-Y plot, uniformly distributed over the operating pH range (not the reagent range). If the curve happens to be variable, then the characterizer should be matched to the most nonlinear curve.

## Compressor Control

Most compressors are fitted with a recirculation valve, allowing some of the compressed gas to be returned to the suction (after cooling) to control the capacity of the machine over a wide flow range. Either the suction or discharge pressure is controlled at the compressor, and the other pressure controlled elsewhere or open to the atmosphere. The recirculation valve then typically operates under constant pressure drop, in which case recycled flow is linear with valve opening. The valve should therefore have a linear characteristic.

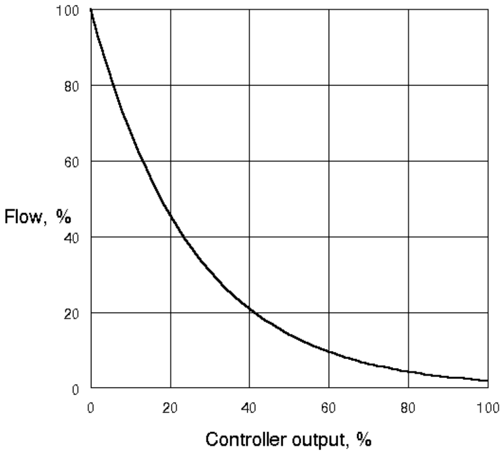

Fig.5. The equal-percentage valve's gain varies directly with flow.

## The equal-percentage valve’s gain varies directly with flow

In many compressor installations, however, an equal-percentage valve has been incorrectly provided1. The gain of this valve varies directly with the flow through it, as shown in Fig. 5. (Note that the valve is reverse-acting, so that it will open on a signal failure.) Under no-load conditions, the valve must recycle all the compressed flow, in which case it will approach full opening, where its gain is highest. The pressure controller must be tuned for stability here. As the load increases toward the normal production conditions, the controller will close the valve accordingly, to a point where its gain will be much lower and therefore the response to upsets will be sluggish.

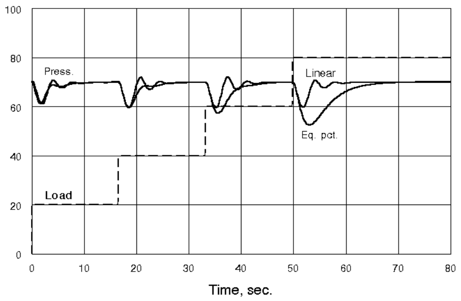

Fig.6. The equal-percentage valve retards recovery at high loads.

## The equal-percentage valve retards recovery at high loads

The response of a reciprocating compressor to a series of step load changes is simulated in Fig. 6, with a linear and an equal-percentage recirculation valve compared. As the load is stepped from zero to 80 percent, the pressure transient with the linear valve remains essentially the same. However, with the equal-percentage valve, the pressure controller had to be tuned at zero load, where the valve gain is highest. Subsequent steps at higher loads show progressively deteriorating response, owing to a reduction in loop gain.

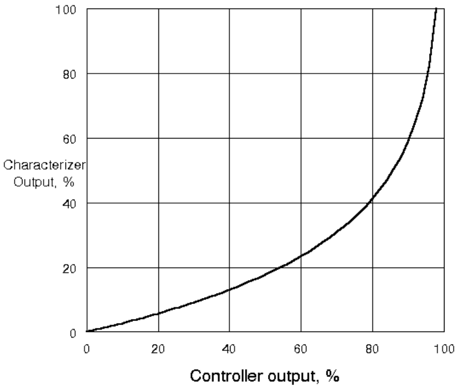

Fig. 7. This characterizer linearizes the equal-percentage valve.

## This characterizer linearizes the equal-percentage valve

A linear recirculation valve should therefore be installed with each compressor. However, in the event that an equal-percentage valve is already in place, the incorrect characteristic can be corrected by inserting a complementary characterizer in the controller-output path. The curve required to linearize the valve of Fig. 5 appears in Fig. 7. Observe that the valve curve is simply rotated 90 degrees to produce the characterizer.

## Fine Points

If the equal-percentage valve were direct-acting, the characterizer curve would have to bend in the other direction, i.e., lying above the diagonal. However, the characterizer should always have a positive gain, so that the controller action remains the same whether a characterizer is installed or not. The same is true for pH characterizers. If the titration curve of Fig. 1 were reversed, for example, by titrating a basic wastewater with an acid reagent, the same characterizer would be used as that shown in Fig. 2.

Remember that retuning of the controller is always required after installing a characterizer, and always in the direction of raising its gain. The gain of the pressure controller in the simulation with the linear valve is over three times as high as with the equal-percentage valve. Therefore control will always be tighter after the characterizer is installed than before.

## References

Shinskey, F. G., “Smoothing Out Compressor Control,” Chem. Eng., Feb. 1999, pp. 127-130.