

Valve response: Truth or consequences

How to specify valves and positioners that don't compromise control.

by Gregory McMillan and Pierce Wu

There have been great achievements in the development of actuators, positioners and control valves this century. However, in some ways, we're living in the past, and regressing to the point where the control valve is limiting loop performance and introducing process variability that can't be eliminated without replacing the control valve. There are many points of confusion, aggravated by the fact that valve positioners may be lying to us, and valve specifications may be misleading.

We didn't have smart positioners and readback of valve position until the 1990s. We were largely flying blind, and we were pretty creative in blaming the sources of oscillations. At the same time, EnTech showed the source of excessive variability could be usually be traced back to poor valves and poor tuning, which we'll see are interrelated. The EnTech specifications led to ISA Standard ISA-75.25-01, "Test Procedure for Control Valve Response Measurement from Step Inputs," and Technical Report ISA-TR-75.25, "Control Valve System Performance." This standard and report were a great step forward and motivated valve manufacturers to provide valves with a better response. However, the necessary additions to valve specification sheets and detailed guidelines were not made. Consequently, users are making as many or more mistakes, possibly because there are many more valves being incorrectly promoted as control valves. Also at play may be the situation where, if cause and effects and guidelines are fuzzy, expertise retires, and people are overloaded, then money rules.

First, we must congratulate those who standardized on a true throttling control valve and were not sidetracked. Those people don't even understand the need for this article, testing or changes to the valve specifications. But even their valves were probably not doing as well as they thought due to lack of readback: not realizing the poor small-step response and the piston actuator resolution limit. Even though the chemical company I worked for nearly my entire career once owned a great control valve company, we were not immune to the problem of select-

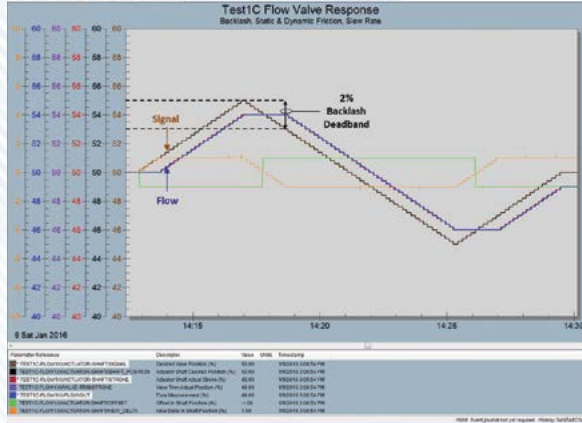
ing valves that were not really control valves, and were not correctly using positioners.

Persistent problems

Lying positioners: Today's digital positioners offer great flexibility in tuning and a wealth of diagnostics. However, this is all based on precise feedback of the actual valve position. This is not possible for a wide spectrum of rotary piping valves posing as throttling valves. Due to high seal friction, the use of key lock or pinned shaft and stem connections, and in some cases linkages, the difference between the actuator shaft position and the actual ball, disk or plug position can be as great as 8%. Often, the feedback for position is on the actuator shaft, and the positioner sees shaft movements 0.5% or smaller, while the actual ball, disk or plug doesn't move for changes in positioner signals less than 8% due to backlash and stiction. Shaft and stem windup occurs where the shaft or stem twists, but the ball, disk or plug doesn't move. The smart positioner generates all kinds of plots and performance metrics saying everything is fine. Everyone is happy with the data except the control loop.

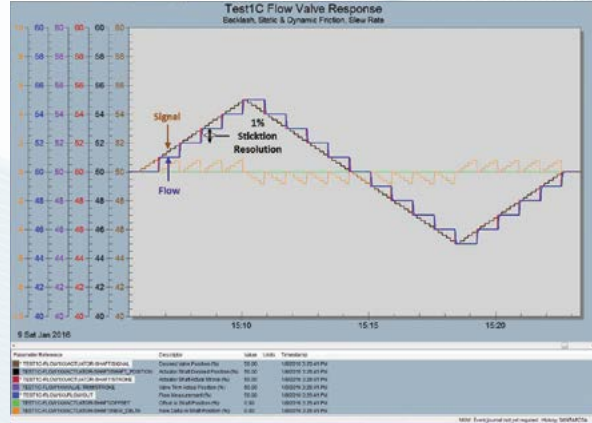
Misleading specifications: Most valve specifications have an entry for leakage but none for valve response. As a result, a valve with tighter shutoff is perceived as better. These are the types of valves that lie to the positioner. Even if feedback was improved, the positioner probably can't prevent the limit cycles we'll see from closed-loop test results that originate from backlash and stiction.

Misleading goals: Piping and process engineers place emphasis on tight shutoff even to the point of thinking a tight shutoff throttling valve can eliminate the need for a separate, automated on-off or isolation valve. And these piping valves are already in the piping spec. Project engineers view these tight shutoff valves as costing less than throttling valves because of the cheaper valve bodies and actuators. Adding a smart positioner may be viewed as a solution to any concern about valve response. The elimination of a separate valve to ensure no leakage as a further bonus clinches the case to use the wrong valve.



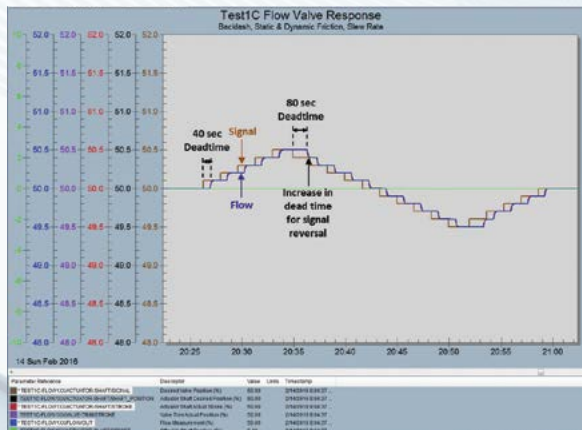
OPEN-LOOP TEST RESULTS FOR 2% BACKLASH

Figure 1: Step changes should be made and then reversed. Ideally, a precise, fast readback or low-noise, high-rangeability measurement is used to determine the dead band.



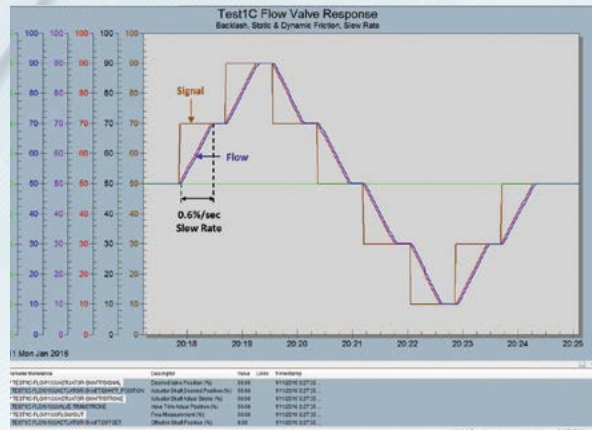
OPEN-LOOP TEST RESULTS FOR 1% STICTION

Figure 2: Step changes should be made small enough to show the smallest change in signal that a valve will consistently respond to. The smallest step is the resolution.



OPEN-LOOP TEST RESULTS FOR POOR POSITIONER DESIGN

Figure 3: Small and large step changes should be made to determine valve response time. For small steps, the time for a smart, sensitive positioner and actuator to reach 86% of final response (T86) is about 1 sec. Poor designs may have a T86 of 48 sec for 0.1% steps doubling to 96 sec for a signal reversal.



OPEN-LOOP TEST RESULTS FOR LARGE, SLOW ACTUATOR

Figure 4: For large step changes (10% or larger), the slewing rate (stroking time) notably affects T86. Here, the valve response after the dead time and secondary time constant is a velocity-limited exponential where rate of change is limited by air actuator exhaust and fill rates.

Tuning confusion: Step tests often use step sizes that are larger than the positioner sensitivity and the valve backlash or resolution, not revealing the source of response problems. Conventional wisdom for an oscillating loop is to decrease the PID controller gain, but this makes the oscillations worse. For limit cycles from backlash and stiction, increasing PID gain will reduce the process variable oscillation period and, in some cases, the amplitude. The limit cycle may not be readily distinguishable from noise

and disturbances, particularly in slow loops where the limit-cycle period is long due to a much-smaller-than-possible PID gain. The lack of fast and precise readback of valve position or lack of a low-noise, high-rangeability flowmeter promotes confusion.

Wrong rules: We know that for cascade control loops, the secondary or lower loop should be much faster than the primary or upper loop. Valve positioners can be viewed as a lower loop, leading to the rule that position-

RESPONSIBLE VALVE RECOMMENDATIONS

- Use on-off and isolation valves for sequences and safety instrumented systems (SIS), and use low-stiction and low-backlash throttling valves with smart, sensitive digital positioners tuned for the application.
- Provide a low-noise and high-rangeability flow measurement.
- If size and process conditions permit, use sliding-stem (globe) valves with diaphragm actuators.
- Make sure valve pressure drop is at least 25% of system pressure drop at maximum flow.
- Make sure actuator is sized for 150% maximum torque and thrust.
- Please add the following requirements to control valve specifications:
 - Resolution = 0.1% to 0.5%
 - Dead band = 0.2% to 1.0%
 - Small step (e.g., step = resolution) 86% response time = 1 to 2 sec
 - Large step (e.g., step = 20%) 86% response time = 1 to 10 sec
 - Minimum valve gain (for installed flow characteristic) = 0.2 to 0.5 %flow/%stroke
 - Maximum valve gain (for installed flow characteristic) = 2.0 to 5.0 %flow/%stroke

ers should not be used on fast loops. As an extension of the rule, theoretical studies using Nyquist plots show that a volume booster should be used. This rule does not take into account that the positioner on a true throttling valve can be tuned for fast proportional plus derivative control, and that most supposedly fast loops have PID execution time and tuning settings that are much slower, relying more on integral action (the classic case being a flow loop). Liquid or furnace pressure loops with special fast-controller execution times of less than 0.1 sec use variable-frequency drives without rate-limiting or dead band to provide a faster response, so the rule is not applicable even here. The wrong rules play into the wrong goals, and people thinking that they can cut project costs by not putting positioners on fast loops.

Diaphragm actuators without positioners. Diaphragm actuators technically don't need positioners to function, but the effect of bench settings and operating pressures, plus backlash and stiction, can cause a disagreement of 25% or more between the PID output and the actual valve position. Furthermore, replacing a positioner with a volume booster on butterfly valves can cause them to slam shut from fluid forces. This is due to positive feedback from

a booster with high outlet port sensitivity and a variable actuator volume from diaphragm flexure. The safe and proper solution for large valves that must be made faster is to put the booster on the positioner output, with the booster bypass valve cracked open just enough to prevent a fast-limit cycle from the positioner.

Unknown performance: Until the advent of the ISA 75.25 Standard and Report, users and suppliers didn't make small step changes during checkout for the valve at operating conditions because they are time-consuming, adding to project costs and schedules. Even now, proper response testing is rarely done. Furthermore, when they generate typical numbers for publication, suppliers tend to not test valve response near the closed position, where the friction from the seat and seal is the greatest.

Erroneous rangeability: Current statements on valve rangeability often are determined with the minimum flow based on a deviation from the theoretical flow characteristic. The minimum controllable flow should include the effects of backlash and stiction near shutoff, as well as the installed flow characteristic based on the ratio of valve-drop to system-drop. Precise valves that aren't oversized with a large valve-to-system pressure-drop ratio have a much greater rangeability. In the gamesmanship to make valve throttling appear to be more energy-efficient, pressure-drop ratios are decreased without realizing the impact on valve rangeability.

Sensible solutions

Period matters: As set by the PID gain and valve dead band and resolution, the period of the limit cycle matters. The process variable oscillations from slower periods aren't as effectively filtered out by volumes downstream. On the other hand, fast oscillations may upset other users of the same process or utility fluid. If it's near the natural frequency of affected loops, the limit cycle may be amplified by resonance from PID action. Even where there is not a limit cycle, which is the case for a flow loop where there is only dead band (no stiction), the slower and more oscillatory response to upsets can be a problem. Using integral action in positioners causes a slower response, and possibly an oscillation from stiction (and even from dead band due to integrating response of the actuator pressure).

Key PID feature: If the PID controller truly has external reset feedback, and a precise and fast readback of actual valve position is available, this feature can be turned on and the PID gain can be increased. In some cases, the limit cycle is stopped. Unfortunately, the most problematic valves, as already noted, do not have accurate readback, and except for large, slow valves, the update of HART secondary variables is not fast enough. Newer I/O systems such as CHARMS may have a fast enough update.

Positioner tuning: The gain and rate settings should be maximized to provide the fastest valve response as tested under actual operating conditions for small as well as large step sizes. The resulting offset should be small enough to preclude the need for integral action. Furthermore, the process PID will correct for an offset. If integral action is used, an integral dead band should be specified to stop a limit cycle from integral action.

Backlash: Step changes should be made and then reversed in direction (Figure 1). Ideally, a precise, fast read-back or low-noise, high-rangeability flow measurement is used to determine the dead band upon a signal reversal. The official definition of dead band is for a signal reversal at 100% open. In reality, the signal reversal should be done at different valve positions. The bowing of the response in different directions is normally less than 0.1%, but one of the many aspects of valve response is to expect the unexpected. Tests for signal reversals at half open generally show the greatest contribution of hysteresis to dead band. Backlash will cause a limit cycle if there are two or integrating responses in terms of valve, process or PID action. Stiction can also contribute to the measured dead band.

Stiction: Step changes should be made small enough to show the smallest change in signal that a valve will consistently respond to (Figure 2). The smallest step is the resolution. The dead band will be increased by the resolution, so this knowledge can help identify the backlash from the dead band. A resolution limit will cause a limit cycle if there's just one integrating response in terms of valve, process or PID action. Eliminating all integrating action will leave an offset. Marginally sized actuators will increase the resolution and dead band, particularly near closed position.

Response time: Small and large step changes should be made to determine valve response time. For small step changes, the sensitivity of the positioner and the actuator come into play. Single-stage and especially spool-type positioners have a slightly faster large-step response time, but they may have a terrible small-step response time. A good, smart, sensitive positioner and a diaphragm actuator should have a time to reach 86% of the final response (T86) of about 1 sec. Poor positioner designs may have a T86 of about 10 sec for 0.2 % steps, increasing to about 50 sec for 0.1% step changes (Figure 3).

For large step changes (10% or larger), the slewing rate (stroking time) notably affects T86. Here, the valve response after the dead time and secondary time constant

is a velocity-limited exponential response, where rate of change is limited by the positioner flow coefficients (Figure 4). A low bleed positioner is bad news. Adding a volume booster on the output of the positioner can solve the problem once it's determined the valve is too slow for large disturbances.

For good and bad designs, and closed-loop test results showing the effect of PID tuning and benefit of the key PID feature, along with war stories and installed flow characteristics, see the addendum, "Valve response: The bigger story."

Final thought

Please, let's work together, following the recommendations (see sidebar) to take advantage of advances in throttling valve technology, and reduce the primary source of variability and confusion. Make the most of dynamic models of valve backlash, stiction, slew rate and response time in process control improvement studies and operator training systems to recognize the effect of valve response on process capability. Let's not let the best go to waste, figuratively and literally, by closing our eyes. We need the truth, or we'll suffer the consequences of the problem becoming more pervasive as pressures on budgets increase. ■

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Valve response: The bigger story

Addendum to Valve response: Truth or consequences

By Gregory McMillan and Pierce Wu

Here we offer a more extensive tour of the sources of poor valve response and the fundamental solutions needed to address the root causes. Temporary fixes are also described to mitigate the consequences until the true solutions can be implemented. The fixes do not fully solve the problem and often have an unexpected downside in terms of the ability to reject disturbances. The fixes should be viewed as just a way of buying some time until a better control valve can be installed. We will find that a low-noise, high-rangeability flow measurement can greatly help diagnose the problem and define the solution, improving the loop performance for all valves as well as particularly problematic applications. The benefits of having flow measurements are even greater than I surmised in the 2/9/2015 Control Talk Blog “Secondary flow loop and valve positioner tips” (www.controlglobal.com/blogs/controltalkblog/secondary-flow-vs-valve-position-control-tips).

Even though control valves and the associated tuning problems are the largest or most frequent source of variability in loops, the full capabilities of advances in actuator, positioner and valve technology have not been effectively utilized due to the lack of understanding and recognition of the problem (as summarized in the accompanying article, “Valve response: Truth or consequences”). Part of the problem alluded to in the article but more fully discussed here is the confusion of terms. A control valve response is nonlinear and non-ideal, posing a challenge for conventional terminology and control theory. Furthermore, the actual valve response is often unknown due to the lack of a readback representative of the actual internal closure member position, and the lack of testing with small step changes including a reversal of direction.

First, let's get on the same page with a more definitive explanation of the terms needed to describe the response and the common alternative definitions that cause confusion. ISA Standard 75.25 and the associated technical report on valve step response have helped considerably. Here, we offer some additional guidance and words of caution. The terms needed are dead band, resolution, 86% response time, and valve gain. An additional term, dead time, is also noted that offers considerable guidance. We highly recommend the use of the ISA publication, “The Automation, Systems, and Instrumentation Dictionary - 4th Edition,” to help eliminate the confusion and better facilitate better communication.

All of the valve response terms are best identified by a step test. The steps must be small to quantify the effects of back-

lash, stiction and poor positioners. The steps must be large to quantify the effect of large actuators. The time in between steps must be large enough to see the response time. We will see that for poor positioners, the dead time can be as large as 40 seconds in the same direction and 80 seconds for a reversal of direction for 0.1% steps. We will also see that for large actuators, the response time can be 30 seconds or more. It is best that these tests be automated. The above article shows how these step tests are done on a trend plot of valve signal, stroke and flow versus time. Here, figures show valve travel versus valve signal for dead band, hysteresis and resolution.

Dead band

If a valve signal is reversed after the last response by the closure member, the reversal in signal necessary to see a change in the closure member position in the right direction is dead band, as shown in Figure A-1. The reversal signal should be done throughout the stroke range (e.g., 10%, 50% and 90%), and the largest dead band documented. This is particularly important because the dead band can be significantly larger due to stiction near the closed position. The official definition of dead band by some valve manufacturers is the decrease in signal needed at 100% to cause the control valve position to start to decrease. This is much less than what is experienced in practice, as seen in Figure A-1. Note that in Figure A-1, the dead band shown is terrible and would be more indicative of a valve without a positioner.

The definition of dead band as the signal reversal required at 100% to reverse stroke leads to unreasonable expectations and an unrealizable valve response. The Fisher 1997 documents “Dead Band vs Hysteresis” and “Dead Band vs Dynamic Error Band” by Floyd D. Jury are excellent references for eliminating the confusion and misuse of the terms dead band and hysteresis. Jury lists the typical sources of dead band as backlash (lost motion from play in connections and linkages) and resolution (stick-slip from shaft windup, packing friction, seal/seat friction, piston actuator O-rings, misalignment, and relays and spool valves in positioners). Dead band tends to be much larger for rotary valves due to backlash, shaft windup and seal friction. Dead band from backlash will result in a limit cycle for closed-loop control if there are two or more integrating responses in the loop. The integrating responses can originate in the automation system (e.g., integral action in a positioner or in a process controller) or in the process (e.g., liquid level, gas pressure, and batch composition, pH or temperature). Note that the use

of integral action in the positioner and the flow controller or integral action in both the primary and secondary process controllers of a cascade control system will cause a limit cycle from backlash even if the process is self-regulating. Options such as integral dead band and external reset feedback can suspend integral action in the automation system.

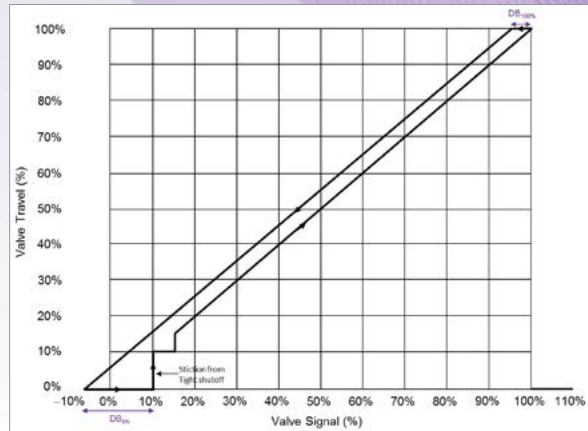
Hysteresis

Hysteresis is the maximum difference in closure member position for increasing and decreasing signals due to the inelastic deformation of springs, bellows and diaphragms. This hysteresis effect by itself is normally insignificant (e.g., $< 0.1\%$). Figure A-2 shows the bowing of the response curve for hysteretic effect. The hysteresis shown in the figure is several orders of magnitude larger than normally seen to illustrate the effect. It is important to know that if the reversal of signal occurred before 100%, the valve would immediately reverse direction. The fact that there is no dead band for just the hysteretic effect means that there is very little detrimental effect to control loops from pure hysteresis. The valve immediately responds to a reversal in signal. The fact that there is a difference in position for an increasing versus decreasing signal due to just the bowing effect is of little consequence in that the positioner or process control loop can correct for this difference. There is a change in the valve gain, but this is usually negligible compared to the effect of the slope of the installed flow characteristic.

Many valve and positioner specifications and publications simply lump dead band and hysteretic effects together as being the largest difference in position for increasing and decreasing signals, calling the result hysteresis. This misconception, plus the practice of defining the dead band for signal reversal at 100% results in misleading statements of hysteresis being much larger than dead band, and hysteresis being the source of most valve response problems.

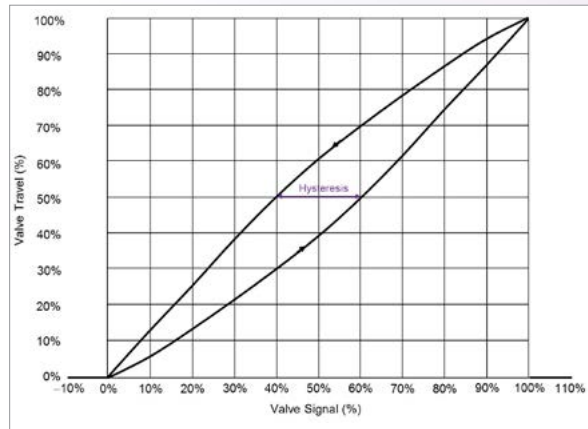
Resolution

If small steps in the same direction are made in a valve signal, the change in signal that causes the valve to respond is termed resolution. The resolution is taken to be about equal to this change in the signal. Figure A-3 shows how resolution results in a staircase response. The amount of signal change before the valve responds is stick. The closure member travel is slip. Slip is not exactly equal to stick, but for the most part, the bigger issue is that any degree of stick-slip will cause limit cycles for closed-loop control unless there is no integrating action anywhere in the automation system or process. Slip can be much larger than stick when opening tight shutoff valves with high seal friction or any valve with plugging or coating at the seat or seal. High temperatures also have been noted to cause expansion of butterfly disks, causing them to stick and then jump to a relatively large position upon opening. There can be quite a delay until the change in actuator pressure is large enough to get the valve to move. The slip can be very large (e.g., 25%) and is really more like an overshoot that a positioner will



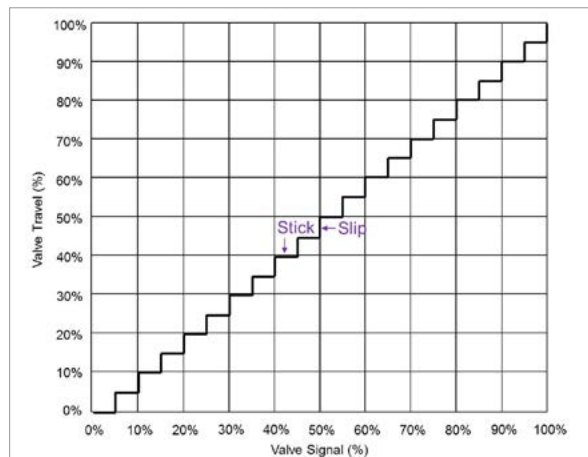
DEAD BAND

Figure A-1: Dead band normally varies from 0.2% to 20%.



HYSTERESIS

Figure A-2: Hysteresis normally varies between 0.02% and 0.2% (hysteresis is exaggerated here to illustrate bowing).



RESOLUTION

Figure A-3: Resolution normally varies from 0.1% to 10% (slip may not equal stick).

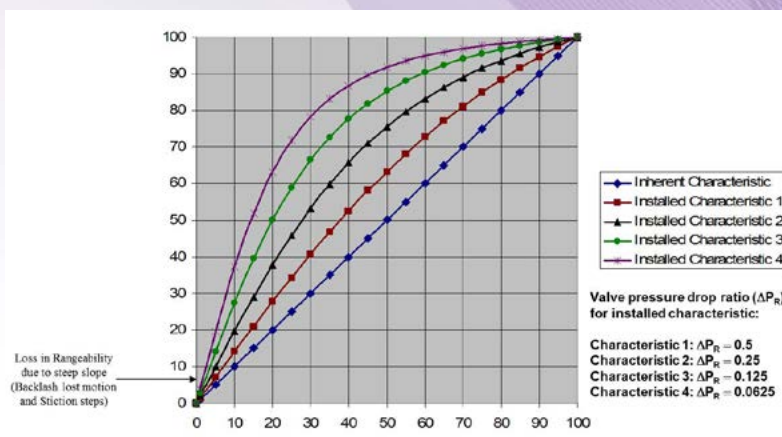
correct in time if readback is indicative of actual plug, ball or disk position. However, the damage may have already been done in terms of surge in flow upsetting the process. The rotary valves where this occurs tend to be quite large.

Resolution has many definitions as in the ISA dictionary and as employed in practice. The resolution term used for valve response is not the same effect you would get from a quantization from analog to digital signal (A/D) converters or a digital actuator or a rack-and-pinion actuator. Quantization results in a travel that is a multiple of the resolution. In other words, if the signal change is larger than the quantization resolution and does not exactly match this resolution, the valve travel is smaller than the signal change. In fact, the ISA use of the term resolution is more like a threshold in that when the signal change exceeds the resolution, the valve fully responds to match the signal change.

Response time

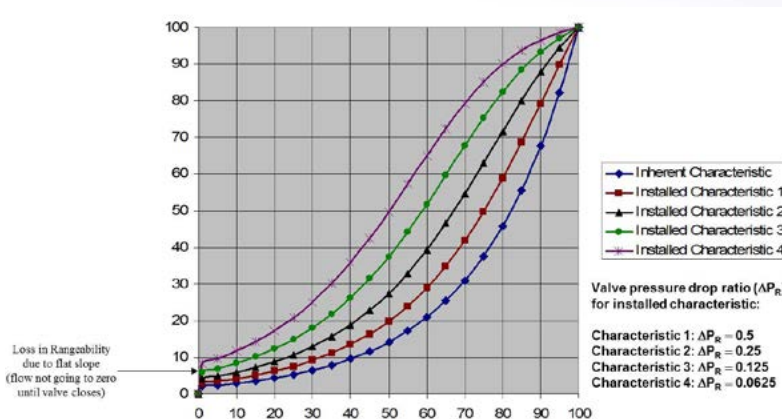
The time to reach 86% of the final response (T_{86}) corresponds in a linear first order plus dead time approximation as being one dead time plus two time constants. Presently, there is no distinction as to whether most of the response time is a dead time or effectively a time constant. The distinction is not critical for slow processes, since the time constant shows up mostly as an increase in total loop dead time. However, the ability to identify secondary time constants by tuning software makes the distinction useful for tight level, composition, pH and temperature control where heat transfer and sensor lags are small. The effect of a valve dead time versus time constant on controller tuning and what the user sees for fast processes, such as flow and pressure, is significant. The open-loop time constant for tuning is the largest time constant, wherever it occurs in the loop. While we would hope it would be in the process, for flow and particularly for liquid pressure, the process time constant is extremely small (e.g., < 1 sec).

I see dead time as the easiest term to identify, in that it is simply the time until the valve starts to move after a sig-



EFFECT OF PRESSURE DROP ON INSTALLED FLOW CHARACTERISTIC FOR LINEAR TRIM

Figure A-4a: A small valve drop to system pressure drop ratio causes a linear inherent flow characteristic to give essentially a quick opening installed flow characteristic, greatly increasing the nonlinearity and discontinuity of stiction and backlash in % flow due to the steep slope near the closed position.



EFFECT OF PRESSURE DROP ON INSTALLED FLOW CHARACTERISTIC FOR EQUAL-PERCENTAGE TRIM

Figure A-4b: a small ratio causes an equal-percentage inherent flow characteristic to excessively flatten out near the closed position, causing a loss in sensitivity below 20% and essentially no flow response below 10%.

nal change larger than the resolution or dead band. Thus, while we are already asking for a lot more to be specified and determined, I would hope identifying dead time would not be viewed as just too much more to do. We will see how identifying the suspected cause and providing a temporary fix and permanent solution depend on knowing how much of the response time is dead time.

Valve gain

The slope in a plot of flow versus % travel (0-100% scale) is the installed

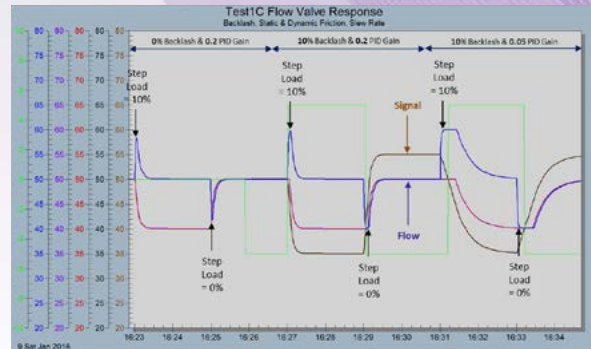
flow characteristic is valve gain. For signal characterization and analysis of the nonlinearity, the flow is in % of maximum (0-100% scale) so that the valve gain is dimensionless. However, in the computation of the open-loop gain that is the product of the valve gain, process gain and measurement gain, the flow needs to be in the same engineering units as used in the process gain. Furthermore, as discussed in the 12/12/2015 Control Talk blog "The hidden factor in our most important loops" (www.controlglobal.com/blogs/)

controltalkblog/hidden-factor-in-our-most-important-control-loops), the valve gain must be in the same units used for the ratio factor in the open-loop gain calculation. While tuning software can identify the open-loop gain, understanding the terms and factors that affect this open-loop gain is important for minimizing the consequences of various nonlinearities. There is a general guidance that the dimensionless valve gain should not vary more than a factor of 4 (e.g., 0.5 to 2.0).

Selection of the best inherent flow characteristic and allocation of the valve drop as a significant fraction of the system pressure drop, as discussed in the 5/6/2015 Control Talk Blog “Best control valve characteristics tips” (www.controlglobal.com/blogs/controltalkblog/best-control-valve-flow-characteristic-tips), can minimize the nonlinearity.

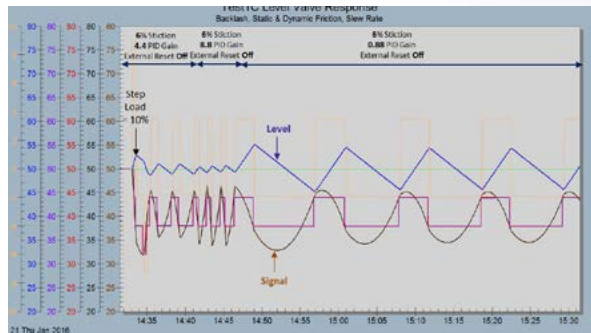
In attempts to show that control valves do not use as much energy as suspected, statements are made that only 5% of the system pressure drop at maximum flow needs to be allocated as the available valve pressure drop. Figure A-4a shows that a small valve drop to system pressure drop ratio causes a linear inherent flow characteristic to give essentially a quick opening installed flow characteristic, greatly increasing the nonlinearity and discontinuity of stiction and backlash in % flow due to the steep slope near the closed position. Figure A-4b shows that a small ratio causes an equal-percentage inherent flow characteristic to excessively flatten out near the closed position, causing a loss in sensitivity below 20% and essentially no flow response below 10%. In both cases, the real rangeability of the valve has been decreased, and the nonlinearity increased. Note here the real rangeability is a function of the slope, dead band and resolution near the closed position. Note also that oversized valves cause a similar loss in rangeability because the resolution and dead band as percentages of flow capacity are greater, and the tendency to operate near the closed position, where stiction and backlash is greater, is more likely.

Signal characterization can reduce the effect of changes in the valve gain, enabling a much more consistent identification of the valve gain and valve time constant for different step sizes and operating points, particularly if resolution and dead band are minimal. Without signal characterization, the controller needs to be tuned for the highest valve gain, resulting in a lower PID gain that reduces loop performance and increases the consequences of backlash and stiction on the parts of the valve flow characteristic where the valve gain is less than the maximum. The 10/20/2015 Control Talk Blog “The unexpected benefits of signal characterizers” (www.controlglobal.com/blogs/controltalkblog/unexpected-benefits-of-signal-characterizers) discusses how characterization makes identification of all open-loop dynamics more exact, freeing up an adaptive controller to focus on the unknown changes in the process dynamics.



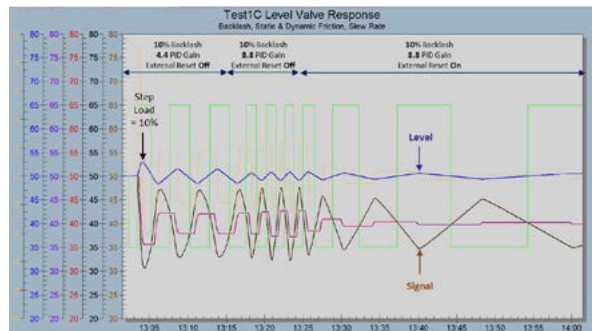
EFFECT OF BACKLASH & PI GAIN ON FLOW LOOP

Figure A-5a: The increase in peak error and integrate error for a step load disturbance is not that much larger for 10% backlash. However, if the PID gain is detuned, the approach back to set-point is much slower due to the additional dead time from the controller output ramping through the dead band.



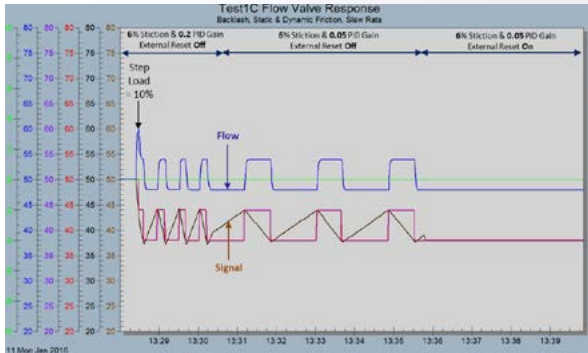
EFFECT OF BACKLASH & PID GAIN ON LEVEL LOOP

Figure A-5b: Increasing the PID gain reduces the amplitude and period of the oscillation of the limit cycle in a level loop for 10% backlash.



BACKLASH & EXTERNAL RESET FEEDBACK ON LEVEL LOOP

Figure A-5c: Turning on external reset feedback can stop the limit cycle.



EFFECT OF STICTION & EXTERNAL RESET FEEDBACK ON FLOW LOOP

Figure A-6a: Only one integrator is needed to cause a limit cycle from stiction. In a self-regulating loop with integral action, turning on external reset feedback at one place in the automation system will stop the limit cycle.

Note that the signal characterization must be done in the controller and the operator must be able to see the signals before and after the characterization.

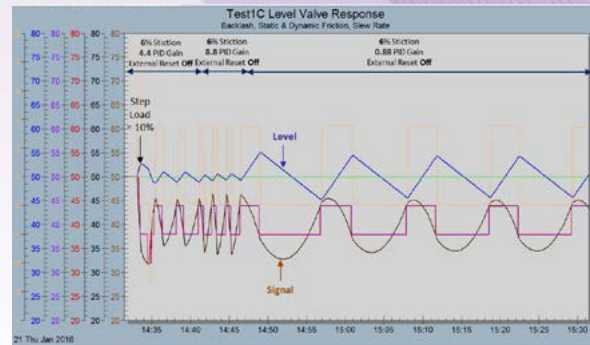
Loop performance

In order to access the impact of common problems with valve response beyond valve gain nonlinearity, tests were conducted to see the effect of backlash, stiction, poor positioner design, and large actuators on flow and level closed-loop response. The flow loop has a fast self-regulating process and the level loop has a slower integrating process response but faster response than most plant level loops to reduce test time. These closed-loop tests reveal the nature and severity of the problem and the ability of tuning and external reset feedback to mitigate the problem.

Closed-loop response for backlash

Two or more integrators are needed to cause a limit cycle from backlash. For just a flow loop, the effect of backlash on the closed-loop response of a well-tuned flow controller is rather minimal. Figure A-5a shows that the increase in peak error and integrate error for a step load disturbance is not that much larger for 10% backlash. However, if the PID gain is detuned, the approach back to setpoint is much slower due to the additional dead time from the controller output ramping through the dead band.

It is important to realize that the use of integral action in a positioner would create a limit cycle in a PI flow controller from backlash. The use of integral action is generally not beneficial for this reason. Also, the position offset, being inversely proportional to gain, is rather small. The positioner gain is typically large and the effect of any position offset is automatically eliminated by integral action in a process controller. There have been cases where the limit



EFFECT OF STICTION & PID GAIN ON LEVEL LOOP

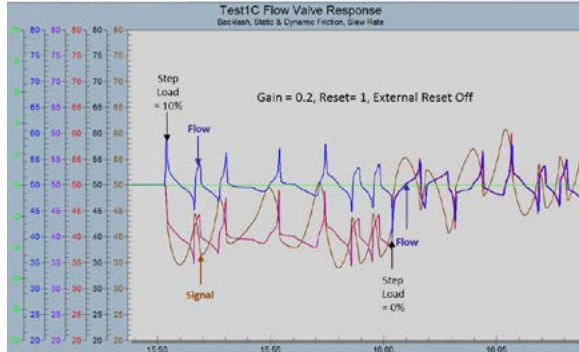
Figure A-6b: For an integrating process, both the amplitude and the period of the limit cycle from stiction are proportional to the controller gain, thus, increasing the level controller gain offers a significant improvement.

cycle from integral action in a positioner was beneficial for a slow loop (e.g., column or vessel temperature control) because the oscillations in manipulated flow were averaged out by the process volume to be closer to the setpoint, enabling tighter control than an offset slowly corrected by the process controller. A better fix would have been a secondary flow tuned for a fast response, and a better solution would have been a valve with less backlash or stiction.

A cascade control system where the primary controller has integral action would also create a limit cycle from backlash. It is important to remember the rule that two integrating responses in a loop, no matter whether in the process or automation system, will create a limit cycle whose amplitude is inversely proportional to the lowest (innermost) controller gain, whether it be the flow loop or positioner.

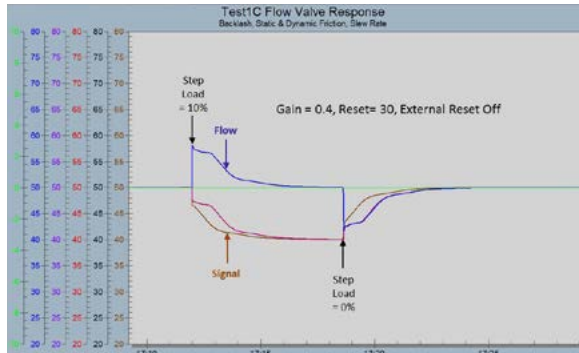
The consequences of backlash are much more problematic for processes that are not self-regulating. Figure A-5b shows the development of limit cycle in a level loop for 10% backlash. An increase in PID gain will reduce the amplitude and period of the oscillation, both beneficial in terms of attenuated oscillations in the process seen downstream. The decrease in amplitude may also reduce interaction, but the decrease in period may or may not help other loops in terms of disturbance and resonance.

Figure A-5c shows that turning on external reset feedback can stop the limit cycle. The PID integral dead band option could stop the cycle, but the user would need to know the dead band so the offset that stops integral action can be set just slightly greater than the maximum possible dead band. Since dead band changes with operating point and process conditions, setting this parameter accurately is rather difficult. A kicker can be used upon signal reversal to cause the valve signal to provide a spike in signal equal to the dead band, but again, getting this accurate and elim-



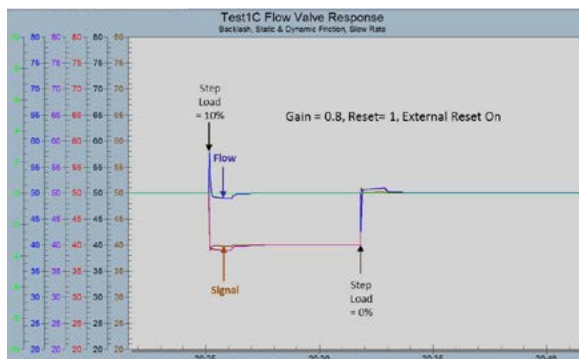
EFFECT OF POOR POSITIONER ON FLOW LOOP

Figure A-7a: Flow loop shows the typical large, irregular oscillations.



POOR POSITIONER, PID GAIN & RESET TIME ON FLOW LOOP

Figure A-7b: Compare to Figure A-7a: Oscillation can be stopped by dramatically increasing the reset time and doubling the controller gain.



POOR POSITIONER & EXTERNAL RESET FEEDBACK ON FLOW LOOP

Figure A-7c: Compare to Figure A-7a: Tight control can be provided using external reset feedback and a high PI gain.

inating the reaction to noise is problematic. If the spike is too large, slip is created, upsetting the loop and causing premature packing wear out.

Closed-loop response for stiction

Only one integrator is needed to cause a limit cycle from stiction. Limit cycles from stiction occur in all types of loops since almost all loops have integrating action somewhere. The amplitude of the limit cycle is proportional to the open-loop gain for a self-regulating process. Increasing the controller gain will reduce the period, but with no effect on the amplitude of the oscillation. In a self-regulating loop with integral action, turning on external reset feedback at one place in the automation system will stop the limit cycle, as seen in Figure A-6a for the flow loop. An offset remains that may or may not be problematic depending the ability of an upper loop to correct for the effect of the offset.

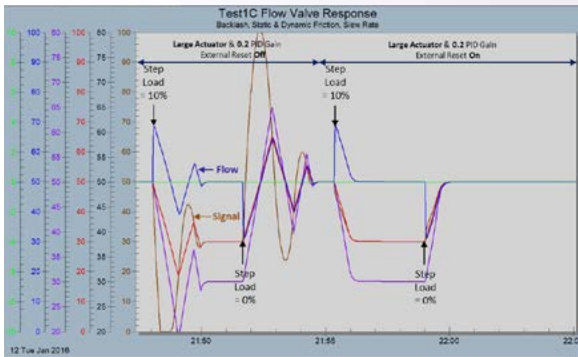
For an integrating process, both the amplitude and the period of the limit cycle from stiction are inversely proportional to the controller gain. Thus, increasing the level controller gain as seen in Figure A-6b offers a significant improvement. Considering that most level controllers are using PID gains much less than permissible, there is an opportunity to significantly mitigate the effect of stiction. Since we did not observe any beneficial effect of external reset feedback on stiction in an integrating process, the test results for this case are not presented.

Closed-loop response for a poor positioner

Spool and single-stage positioners have a dead time that dramatically increases as the step size decreases. For our test case, the dead time increased from 10 seconds to 40 seconds for a decrease in step size from 0.2% to 0.1%. This dead time was double for a reversal in direction.

The good news, if there can be good news for this situation, is that increasing the reset time can stop the oscillations, and using external reset feedback and a very high PID gain up to a limit of being the inverse of the open-loop gain, can essentially eliminate the effect seen. Of course, the best solution is to use a smart, sensitive positioner with high fill and exhaust rates.

Figure A-7a shows the large irregular oscillations for a flow loop. Figure A-7b shows that dramatically increasing the reset time and doubling the controller gain can stop the oscillations. Figure A-7c shows that the use of external reset feedback and a high PI gain can provide tight control. This result is, in a way, analogous to that discussed in the 7/6/2015 Control Talk Blog “Batch and continuous control with at-line and offline analyzers tips” (www.controlglobal.com/blogs/controltalkblog/batch-and-continuous-control-with-at-line-and-offline-analyzers-tips) on how an enhanced PID simplifies tuning and stops oscillations in a composition control loop where the dead time from the analyzer can be extremely large and variable.



FLOW LOOP: LARGE ACTUATOR & EXTERNAL RESET FEEDBACK

Figure A-8a: Turning on external reset feedback will eliminate the oscillation for both flow and level loops, here shown on a flow loop.

Closed-loop response for large actuators

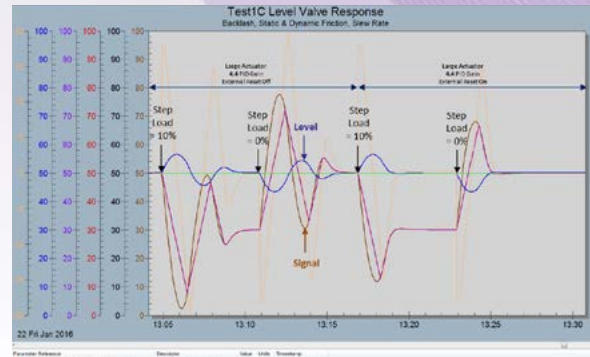
If you have a good positioner and valve design, the response time can be too slow for large step changes and large actuator volumes. Higher-pressure actuators can help reduce the actuator size needed, however, for loops with extremely fast response time requirements for large changes in valve signal, the pre-stroke dead time and stroking time can be excessive. The response is a rate-limited, second-order exponential where the rate limiting (slew rate) is set by the stroking time, determined by positioner flow coefficients (Cv) and the required actuator volume and travel. The response time increases with step size due to the rate limiting. Figures A-8a and 8b show that turning on external reset feedback will eliminate the oscillation for both flow and level loops. A better solution is to install a volume booster on the output of the positioner with its bypass opened just enough to stop the fast oscillations from the positioner changing the pressure incredibly faster when supplying and exhausting a small booster volume rather than the large actuator volume. The bypass diverts some of the air flow to occur between the positioner and the actuator, slowing down the pressure response, making it stable.

War stories

Here are just a few of the many experiences I have had with valve response. They illustrate how I learned the hard way that process control publications and valve specifications were misleading.

War story #1 - Positioners on fast loops

- **Contractor Lead (1976):** For new world's largest plant, let's save money and not use positioners on fast loops per white paper.



LEVEL LOOP: LARGE ACTUATOR & EXTERNAL RESET FEEDBACK

Figure A-8b: Turning on external reset feedback will eliminate the oscillation for both flow and level loops, here shown on a level loop.

- **Plant:** Good grief - valves are not open when PID output is 25%. There seems to be no correlation with PID output and valve position.
- **Greg:** Put positioners on all of the valves.
- **Plant:** Fast loops work great and valve position matches PID output.
- **Fellow (1990):** For all of the new plants in Asia, let's save money and not use positioners on fast loops per white paper.
- **Greg:** No way, the concern of Cascade Rule violation is not an issue here.

War story #2 - Boosters for surge control valves

- **Greg (1984):** Nyquist Plot study says on fast loops, boosters instead of positioners should be used. This surge control loop must be incredibly fast. Compressor can go into surge in less than a second. Take off the positioner and put on this new volume booster.
- **Tech:** You need a positioner but I will do what you say.
- **Plant:** Surge valve slams shut upon opening causing shutdown.
- **Tech:** See how I can move this 24-in. butterfly with only a booster by grabbing the stem? I can't move the adjacent valve with positioner.
- **Greg:** Put positioner back on, put booster on positioner output and open booster bypass just enough to stop high-frequency oscillation.
- **Plant:** Valve operation is fast and smooth.

War story #3 - Boosters for furnace pressure control valves

- **Greg (1986):** This phosphorous furnace pressure can ramp off-scale in a couple of seconds. We have a special, fast controller execution rate and minimum damping

transmitter. We need valves with a response time of less than two seconds.

- **Supplier:** Here are the valves all set up in our test facility. They are as fast as you wanted. We replaced the positioners with volume boosters.
- **Greg:** Look how I can grab the shaft of these 20-in. valves and move them.
- **Supplier:** Hmm, you don't look that strong. Let's check with an old timer.
- **Greg:** Please put the volume boosters on the output of the positioner and crack open their bypass valves just enough to stop high-frequency cycle.
- **Supplier:** You are right. Old timer dug up 1958 article confirming your decision.

War story #4 - Phosphorous slurry control valves

- **Plant:** We have our favorite new ball valves with the latest smart positioner. The positioner diagnostics and readback shows the valve is responding precisely to the signal but the process is oscillating. There is no flow measurement so we think the oscillations are from elsewhere.
- **Greg:** Let's look at ball movement in shop. The actuator shaft that is read back moves in response to signal, but the ball does not move for changes less than 8% due shaft windup from a keylock shaft-to-stem and a pinned stem-to-ball connection, and excessive friction of seal to achieve the tight shutoff. You have an isolation valve posing as a throttle valve.

War story #5 - Reactor air pressure control valves

- **Shop:** We have the plant's favorite low-leakage butterfly valves from their piping specification with the latest smart positioner. The positioner diagnostics and readback shows the valve is responding immediately and precisely. Here are the screen prints. It is ready for installation.
- **Greg:** Let's put a travel gage on the disk. Good grief! The actuator shaft that is read back moves in response to signal but the disk does not move for changes less than 8% due shaft windup from a keylock shaft-to-stem and a pinned stem-to-disk connection, and excessive friction of seal to achieve the tight shutoff. You have an isolation valve posing as a throttle valve.

War story #6- pH control valves

- **Greg:** Great! I see where you have throttling control valves with better than 0.4% dead band and 0.2% resolution that will meet my control requirements for a customer's pH loop.
- **Supplier:** The dead band is actually 0.8% and the resolution is 0.4% based on the size of actuator stocked to make the valve cheaper for competitive bids.
- **Greg:** Can we order the valve with a larger actuator?

- **Supplier:** It will become a special and cause the delivery to be 12 to 16 weeks.
- **Greg:** This is too late to meet the plant requirements.
- **Supplier:** You can order control valve designed for research labs.
- **Greg:** No thanks! The diameter of the stem is so small the stem can easily be bent in a plant.

Best Design

All control valves:

- Actuator thrust or torque > 150% of maximum requirement
- Valve capacity not greater than 125% of maximum flow requirement
- Valve drop to system drop ratio greater than 0.25
- Diaphragm actuator (new high-pressure model for large valves) or digital actuator
- Large shaft and large stem diameters
- Tuned, smart, sensitive positioner with high fill and exhaust rates (large fill and exhaust Cv)
- Minimum packing friction
- Class 1 leakage
- Volume booster on positioner output as needed to reduce stroking time
- Fast, precise readback

Sliding stem (globe) valves:

- Flow to open
- No contact with seat after valve opens

Rotary (ball, plug, butterfly) valves:

- Rotary positioner
- Tight (e.g., splined) actuator shaft-to-valve stem connection
- Short shaft length
- Integrally cast stem with ball or disk (no pinned connection)
- No contact with seal after valve opens

Summary

The value of flow measurements goes way beyond what has been expressed for feedforward control in the Control Talk Blog. Flow measurements can greatly help identify the installed flow characteristic of the valve, provide valve diagnostics, deal with lying positioners found on on-off valves posing as throttle valves, compensate for pressure disturbances, and reduce the consequences of poor valve response.

There is a counterintuitive situation, where the PID gain should be increased when oscillations are observed. A higher PID gain will reduce the process variable (PV) amplitude of limit cycle periods from backlash in all processes and from stiction in integrating processes. A higher PID gain also reduces the dead time from dead band and resolution limits, and increases the step size from one execution of the PID to another, particularly important for poor positioners.

In the closed-loop test results, the initial tuning used

lambda equal to three dead times with self-regulating tuning rules for the flow loop and integrating process tuning rules for level. The dead time was 1 second and 10 seconds for the flow and level loop, respectively. The self-regulating process gain was 1.0 %PV/%MV in the flow. The integrating process gain was 0.01 %PV/sec/%MV (0.01/sec) in the level loop (faster than normal to reduce test time). The manipulated variable (MV) is the valve signal. The installed valve characteristic was linear. Signal characterization can be used for nonlinear valves, enabling a higher PID gain, which is important for reducing dead time and limit cycle amplitudes. Signal characterization eliminates the need to reduce the PID gain for the steepest slope of the installed flow characteristic. Without characterization, faster movement on the steep part can lead to the PV reaching 63% of its final value, resulting in a smaller than actual time constant and a smaller than useful reset time for lambda tuning.

An oscillation in a loop with a self-regulating process, such as a flow, is due to backlash if the return to setpoint or oscillation is slower as the PV gets closer to setpoint. The PV and PID output oscillations are rounded. A PV oscillation due to just backlash can disappear as the PID gain is increased. In fact, for the test case, an oscillation only appeared if the PID gain was a factor of 4 smaller than what would be suggested by lambda tuning for lambda equal to 3 dead times. There is no limit cycle. In contrast, an oscillation in this loop due to stiction is a limit cycle (will not decay) and is characterized by a square wave if the PV response is fast, like flow, with a ramping back and forth of the PID output. An increase in PID gain will not reduce the PV amplitude of the limit cycle, but will decrease the period. The PV amplitude of the limit cycle is solely dependent upon the process gain. Turning on external reset feedback will stop the limit cycle with an offset dependent upon the stiction and final resting value of PID output.

The behavior of a loop with an integrating process, such as level, will develop a limit cycle for either backlash or stiction. In both cases, the PV (e.g., level) will ramp back and forth and the PID output is rounded. The cycle PV amplitude and period decreases as the PID gain is increased. If the oscillation is due to backlash, turning on external reset feedback with a high PID gain can make the PV amplitude so small for a high PID gain that the PV oscillation is unnoticeable, hidden within sensor noise or sensitivity.

An oscillation in a self-regulating process and in an integrating process due to a poor positioner can be made to decay by a dramatic increase in the reset time. A modest increase in the gain helps here as well as in the case of a valve with a large actuator. In all of the cases for a poor positioner or large actuator, the use of external reset feedback with the modest increase in gain offers a tremendous improvement with the reset setting left at its original value.

Integral action tends to accentuate problems since it has

not sense of direction or movement. For poor positioner designs, the reset time needs to be greatly increased. The use of external reset feedback with a fast and precise read-back can stop limit cycles by suspending integral action. In all cases, the reset time can be left at the original value for moderately aggressive tuning (lambda = 3 dead times). The PID gain can be increased. In the case of a poor positioner on a fast, self-regulating process (e.g., flow), the PID gain can be dramatically increased up to the inverse of the open-loop gain. If external reset feedback is not available, inserting a filter time constant larger than the dead time in a flow loop gives a larger PID gain as well as a slower reset time for Lambda tuning. Normally, filter time constants greater than 20% of dead time should not be used.

The use of lead-lag on the PID output or in the positioner was not tested. It is conceivable that a lead time greater than the lag time might help the valve signal get through backlash or stiction faster. The cases where an increase in PID gain helped are candidates for the use of such a lead-lag.

The real solution is to put the valve response requirements in terms of dead band, resolution, 86% response time, dead time and valve gain on the control valve specification, and make sure the valve meets these specifications. Control valves must not be oversized nor actuators be marginally sized.

For isolation, on-off valves designed for tight shutoff should be used. For throttling, control valves designed for low backlash and low friction should be used with smart, sensitive positioners with large fill and exhaust Cv tuned for fast proportional action. Volume boosters should be put on valve positioner outputs as needed to speed up the large step response. Dynamic models should be used to better understand valve response in general. In specific applications, these models can quantify the effects of valve response on the process and the tuning needed to minimize the consequences. The results can provide justification for better control valves. Finally, automated small-step response tests should be done at operating conditions, and at the minimum operating valve position expected. ■

Resources:

McMillan, "Tuning and Control Loop Performance", 4th ed., Momentum Press, 2015

McMillan, "Essentials of Modern Measurements and Final Elements in the Process Industry", ISA, 2010

McMillan, "Key design components of final control elements", InTech, March-April, 2010

McMillan, "Improve Control Loop Performance", Chemical Processing, October, 2007

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