A simple method to determine control valve performance and its impacts on control loop performance

Michel Ruel p.eng., Top Control Inc.

Keywords

Process optimization, tuning, stiction, hysteresis, backlash, dead time, positionner, performance.

Summary

A control loop consists of the process, measurement, controller, and a final control element (valve, damper, etc. and its associated equipment such as positionner, I/P). Optimal process control depends on all of these components working properly. Hence, before tuning a loop, one must verify that each component is operating properly and that the design is appropriate.

Choosing the optimal PID tuning should be done after making sure all of the other components are working properly. Our experience in the field has shown us that the impact of good tuning is more important than equipment performance itself. We will discuss a method to determine if the valve is performing well and this is done while the process is running. We will demonstrate how a poorly performing valve will have a minimal effect on control loop performance if the tuning parameters are not optimal. However, if a control loop is tuned to achieve performance, the control valve behavior will have a major impact on performance.

Introduction

In North America, the majority of control loops have not been tuned to reach optimal performance. Very often, during installation, the tuning parameters are left as the manufacturer defaults. When problems occur with control loops, people often tend to reduce the tuning parameters, as this is the quickest way to reduce instability.

For example, if a valve has some backlash, the loop will have a tendency to oscillate. If the technician reduces the tuning parameters, he will then hide the problem (which will get bigger and bigger as time goes by) and will also make the loop slower to respond.

Tuning should be considered a major part of a control loop. Why spend a lot of money on expensive equipment if we only use it to fraction of its potential?

It is hard to identify when a valve is damaged or needs to be replaced, if the tuning has not been done correctly.

In this article, disturbance responses of perfect and “real world” valves will be analyzed using aggressive and sluggish tuning. The results will show that tuning has a major impact on the performance of control loops.

Many criteria can be used to evaluate control loops:

- stability,
- overshoot,
- removing quickly a disturbance,
- etc.

Valves, non linear devices

When a command has been given to a control valve for a new position, the behavior of the valve will vary depending on its position, its direction and the amplitude of the signal.

Examples:

1. When the position change is small, the dead time of the valve is generally longer than it would be for a bigger change. In fact, the positioner must supply enough to overcome stiction. When changes are more important, the behavior of the valve is similar to a linear system.

2. When the signal is very big, saturation will prevent the valve from moving faster than a set pace.

3. Certain valves will not behave the same when they are opened and when they are closed.

4. Since the torque that moves the valve varies in accordance with the opening and the process conditions, the valve's dynamic behavior is not the same on the entire range.

5. Backlash causes hysteresis.

6. Seals and seats cause stiction.

7. The positioner causes overshoot.

8. The inherent characteristic curve of the valve is often ignored during selection. Instead of reducing the gain variations according to the load, it increases them.

The effects of control valves

Dead time

When a simple position change is made, the dead time is generally long. Indeed, the positioner provides a small airflow and pressure slowly builds up.

If a positioner is not tuned to be sensitive, the dead time will be even longer.

Time constant (tau)

The valve time constant is due to the actuator reservoir which fills with air as a first order system (time constant). If a positioner has been tuned too loosely, the time constant will be longer. Many manufacturers offer positioners with different capacities, depending on the size of the actuator. When bigger changes are made, the speed is limited and the time constant appears longer.

Hysteresis, Backlash, Dead Band

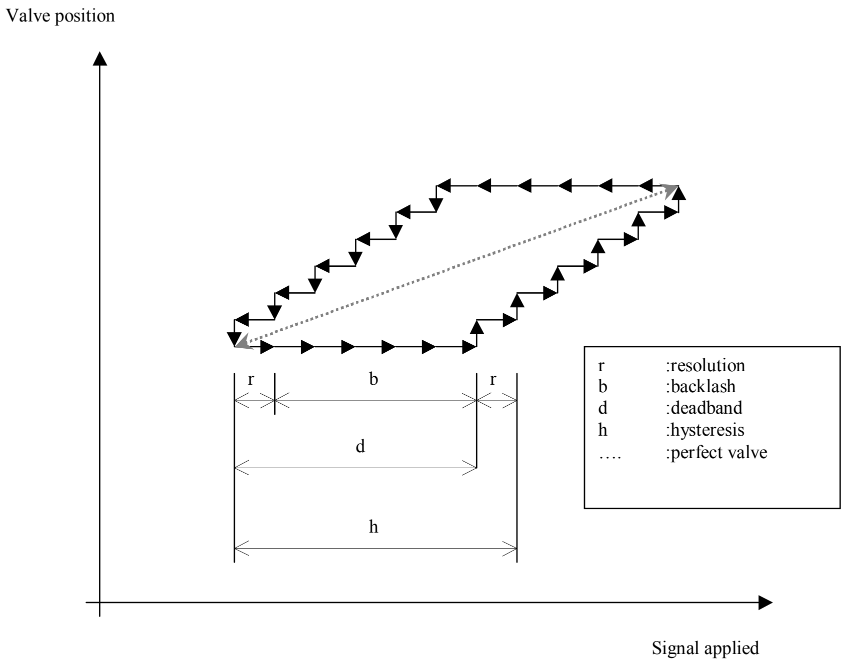
The position of a valve with hysteresis will vary whether the signal increases or decreases. Hysteresis usually comes from backlash, but is can also be caused by non-linearities such as seals or friction. Hysteresis provokes oscillations and reduces performance. When a change occurs, hysteresis will also add to the dead time.

*Backlash :*If mechanical parts are loose, when reversing direction, the valve movement will be different from the signal.

*Resolution:*The resolution is the smallest increment of input signal in one direction for which movement of the valve is observed. Resolution is caused by a sensor like a wirewound resistor; each loop of wire produces an output jumping each time a new loop is reached. Also, digitizing a signal will do the same. For example, the resolution for an 8 bits system is 1/256=0.4%.

Figure 1 illustrates the terms: dead band, resolution, backlash and hysteresis.

Figure 1



If resolution is perfect, backlash=deadband=hysteresis.

Figure 2 illustrates how a valve with backlash responds. Figure 3 shows how the valve responds to bumps.

Figure 2

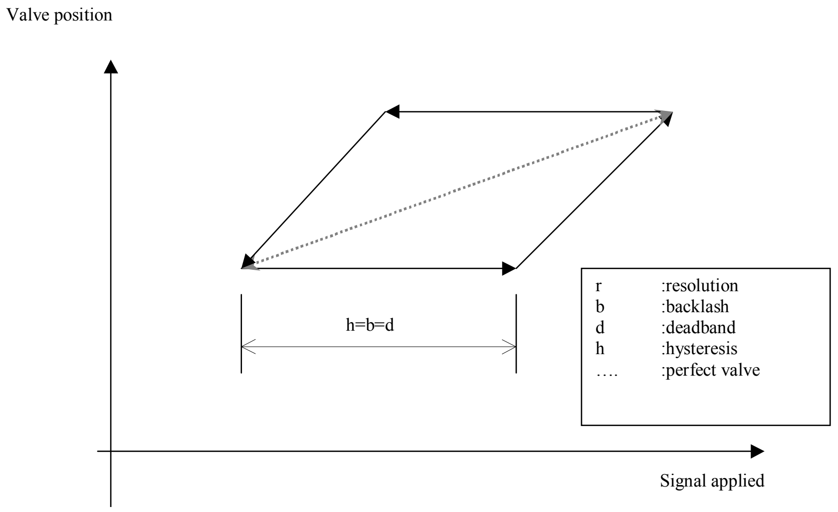
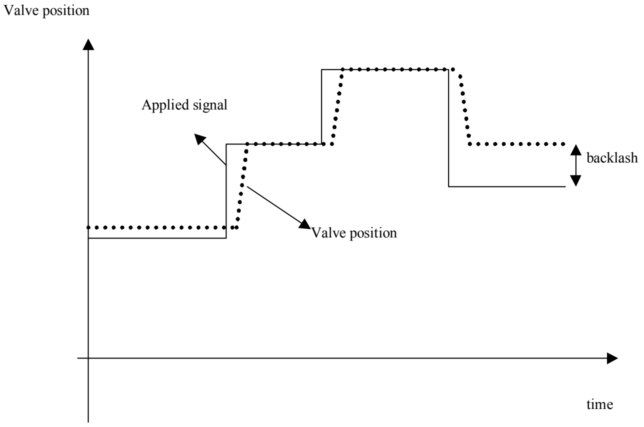


Figure 3 illustrates also how to determine the backlash in a valve. If the backlash is zero, the valve position and hence the process variable will go back to the previous position. Ideally, backlash in a valve is zero, but in most valves, it is near 1 %. On most processes, a backlash of 2 or 3 % is acceptable if the controller is not tuned too aggressively. Such backlash adds dead time to the loop and reduces performance. Usually, the backlash and hysteresis are almost equal.

Figure 3



Stiction

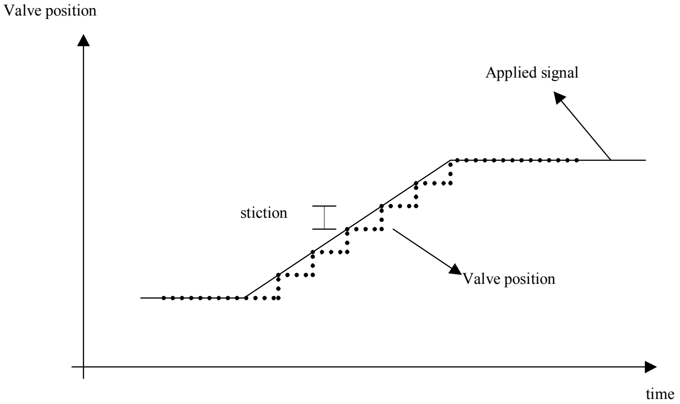
Anything that comes in contact with the moving parts of a valve will create friction; the seats, the seal, etc. It is not possible to move a valve with stiction unless the command is big enough to overcome this friction. The problem becomes more obvious when an actuator is weak. When stiction occurs, the dead time will be longer as friction must be overcome before the valve will move. Stiction is the resistance to the start of motion, usually measured as the difference between the driving values required to overcome static friction upscale and down scale.

The word stiction is made from the words **stic**k and fric**tion**.

For example, it is sometimes hard to move a piece of furniture. However, you apply pressure and it suddenly gives, moving rapidly. Similarly, stiction causes the piston of an air cylinder to suddenly lurch forward at the start of a stroke or to move jerkily during its travel.

Stiction is caused when the static (starting) friction exceeds the dynamic (moving) friction inside the valve. Stiction describes the valve's stem (or shaft) sticking when small changes are attempted. Friction of a moving object is less than when it is stationary. Stiction can keep the stem from moving for small control input changes, and then the stem moves when the force is enough to free it. The result of stiction is that the force required to get the stem to move is more than is required to go to the desired stem position. In presence of stiction, the movement is jumpy.

Figure 4



Positioner overshoot

When overshoot occurs, the valve moves too far and this can destabilize the loop, particularly if the loop is fast.

Volumetric coefficient Cv

The Cv must be chosen so the process gain is close to one. If the Cv is too small, the measure will never reach a sufficient value. However, if the Cv is too big; all the valve's defects will be amplified.

Inherent characteristic curve

If the proper inherent characteristic curve is not chosen, the process gain variations may be amplified rather than reduced.

The impact of the valve on the process model

For fast processes such as flow and pressure, the dynamic response of the valve (dead time, time constant, positioner overshoot) will be important. However, hysteresis, stiction, Cv and the inherent characteristic curve always influence the behavior and the performance of the loop.

Criteria for good functioning

Before setting the parameters of a controller, it is important to determine if the characteristics of the loop would allow sufficient performance.

Four 3s rule

	Practical	**Ideal**
Process gain	$Gp < 3$	**1**
Linearity	$Gp_{\max} / Gp_{\min} < 3$	**1**
Hysteresis	$Hyst < 3\%$	**0**
Noise band	$N.b. < 3\%$	**0**
Stiction	<<1%	**0**

Process gain

If the process gain is too big, the problems of the valve will be amplified and the controller will have to be detuned. Performance will therefore be reduced.

Solution: Recalibrate the transmitter or reduce the Cv (valves are often too big).

Linearity

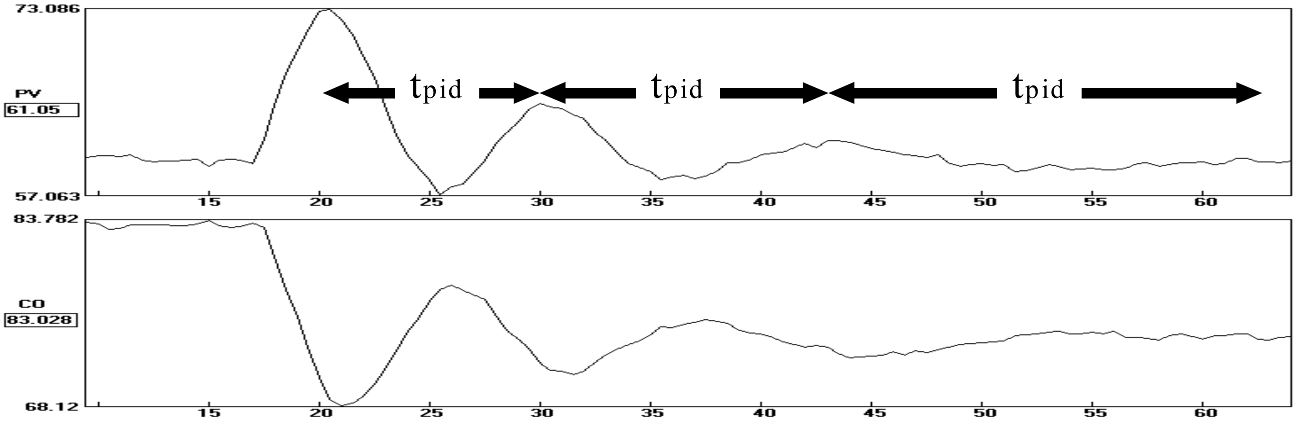
The loop must be tuned within the range where maximum process gain is reached. However, this will decrease performance about the point where the process gain is minimal.

Solution: Change the inherent characteristic curve of the valve or use a characterizer between the controller and the valve.

Hysteresis

Large hysteresis will cause the dead time to increase when the output signal's amplitude is weak. This increase makes for a longer period (damped sine wave), since the process variable is close to the setpoint. The loop will then be destabilized.

Figure 5

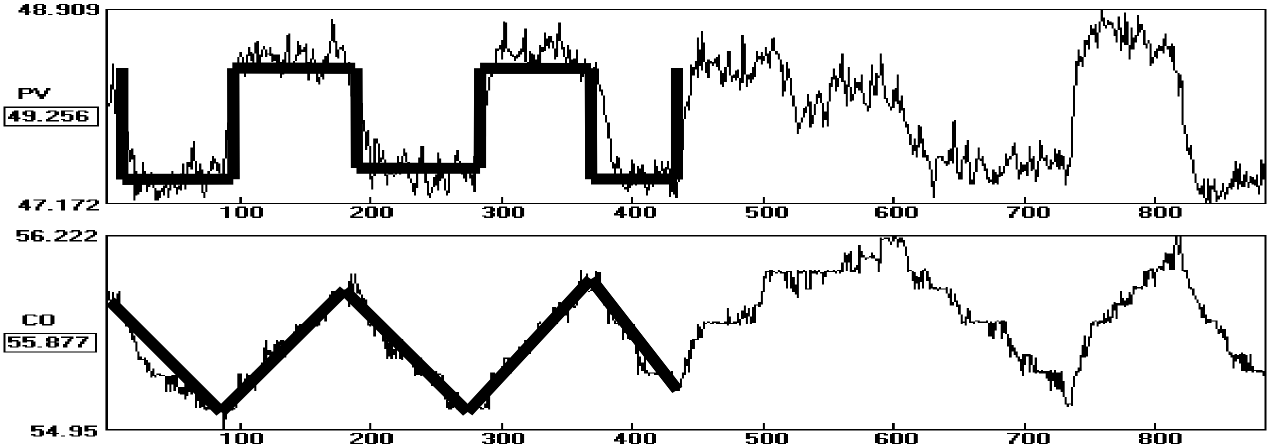


Solution: fix the valve/positioner.

Stiction

If the valve sticks, the controller output will slowly increase until the valve finally moves. If the stiction is large, the valve will then move too much This will cause the controller to reverse and try to move the valve in the opposite direction; however, stiction will create an overshoot again. The controller output looks like a sawtooth and the process variable looks like a square wave.

Figure 6



Solution: fix the valve/positioner.

Noise

If too much noise is present, the loop cannot be tuned aggressively or the controller will amplify this noise. This will cause the positioner to hunt back and forth, leading to a shorter valve life.

Solution: Eliminate or reduce everything that causes noise. The valve movement will be reduced by choosing an adequate filter.

Tuning of the controller parameters

The goal is to obtain a compromise between performance and stability.

To obtain performance, it is best to use large values for each parameter (P, I, D).
To obtain stability it is best to use low values for each parameter (P,I,D).

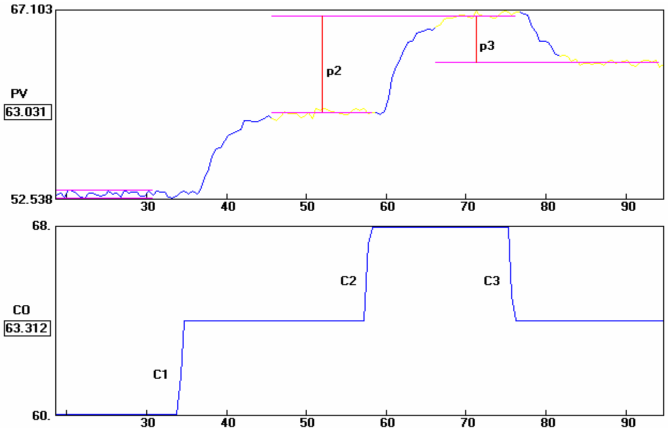
A loop is robust when stability can be maintained while the characteristics of the process are changing. However, it is often possible to improve the robustness as well as the performance of a control loop. This happens when the proportional gain is too high (not robust and unstable) and the integral time is too long (long response time).

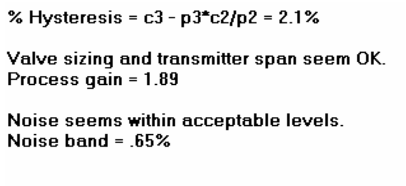
Tests to determine the process characteristics and analyze the equipment

To determine the process characteristics, it is necessary to do small bumps then a ramp. These tests are necessary to evaluate hysteresis (backlash and dead band), stiction and process gain. Also, asymmetry will be verified looking at the process moving in both directions. If possible, a series of bumps will be done to verify if the process is linear.

Hysteresis test, Noise, Process gain

Figure 7




% Hysteresis = c3 - p3*c2/p2 = 2.1%

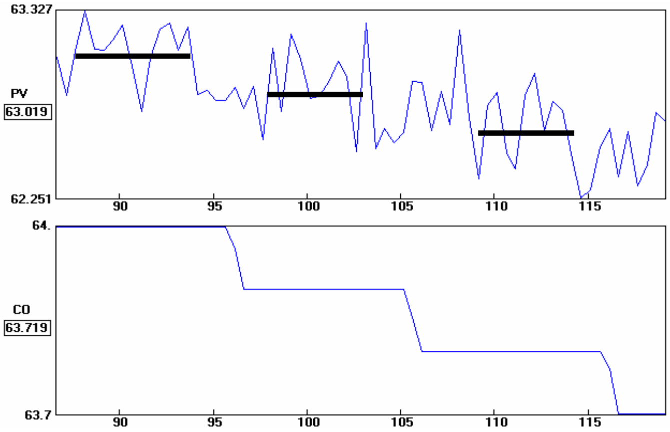
Valve sizing and transmitter span seem OK.
Process gain = 1.89

Noise seems within acceptable levels.
Noise band = .65%

Before C1, to determine noise,
C1 removes the backlash,
C2 to determine process gain,
C3 to determine backlash.

Stiction test

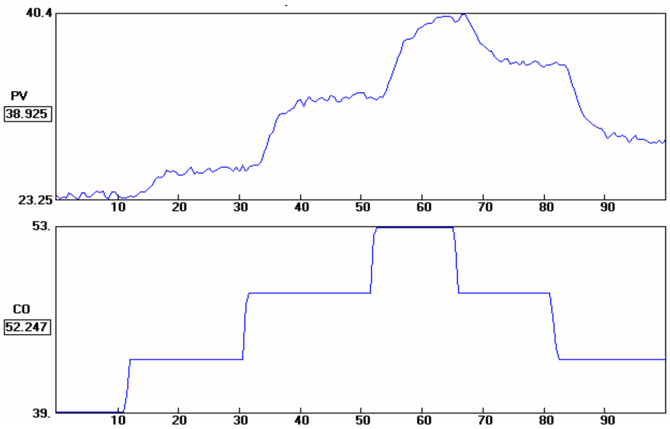
Figure 8



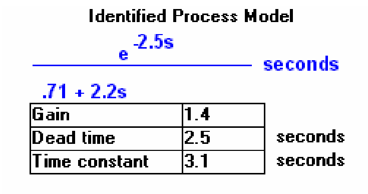
The process variable moved after the 0.1 % change in the control output. Stiction is less than 0.1%.

Asymmetry test

Figure 9



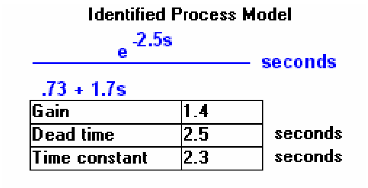
Process increases


Identified Process Model

$$\frac{e^{-2.5s}}{.71 + 2.2s}$$ seconds

Gain	1.4	
Dead time	2.5	seconds
Time constant	3.1	seconds

Process decreases


Identified Process Model

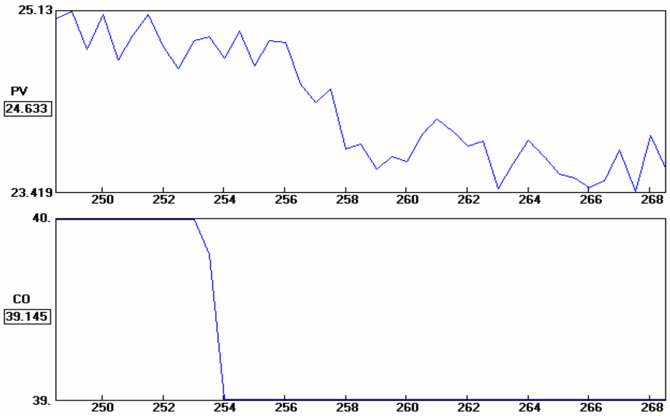
$$\frac{e^{-2.5s}}{.73 + 1.7s}$$ seconds

Gain	1.4	
Dead time	2.5	seconds
Time constant	2.3	seconds

The process is similar in both directions

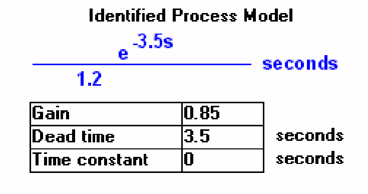
Small change (1 %) model

Figure 10



Small change model

Process decreases


Identified Process Model

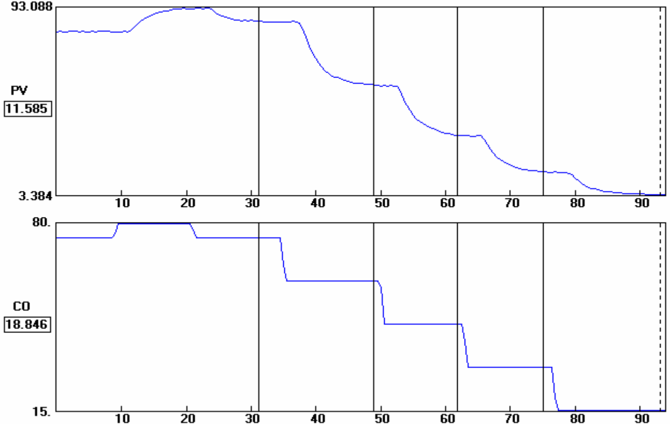
$$\frac{e^{-3.5s}}{1.2}$$ seconds

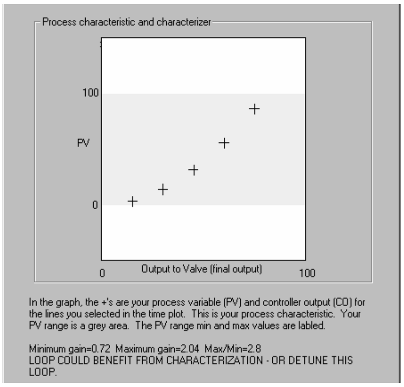
Gain	0.85	
Dead time	3.5	seconds
Time constant	0	seconds

The process model is different for a small change. Typically, the dead time is longer for a small change.

Linearity test

Figure 11





In the graph, the +'s are your process variable (PV) and controller output (CO) for the lines you selected in the time plot. This is your process characteristic. Your PV range is a grey area. The PV range min and max values are labled.

Minimum gain=0.72 Maximum gain=2.04 Max/Min=2.8
LOOP COULD BENEFIT FROM CHARACTERIZATION - OR DETUNE THIS LOOP.

This loop is not linear, but this is acceptable.

Characteristics of the valves

Speed

A fast valve is required when:

- the loop is fast
- the tuning of the controller has been chosen to maximize performance (aggressive or moderate tuning)

Precision

A precise valve is required when:

- performance is important
- the loop is stable (and the loop's parameters have been set correctly).

Setting the parameters

Derivative has not been used in the simulation, since Lambda based tuning never uses it. In many processes, the use of the derivative will greatly increase performance when using moderately aggressive settings. The derivative also reduces problems caused by the control valve.

Tuning	**Goal**	**Pros**	**Cons**
Aggressive	Small errors	Performance	Not robust Oscillations
Moderate	Good compromise	Performance and robustness	
Lambda (sluggish)	No overshoot after setpoint change	Simple Stable	Performance varies

Simulation

The following process was simulated to observe the impacts of stiction and hysteresis.

Gp=1, Dead time = 1 s, Time constant = 3 s, a white noise with a standard deviation of 0.1 % is added to the process variable.

The displayed values are in %.

Three situations were simulated:

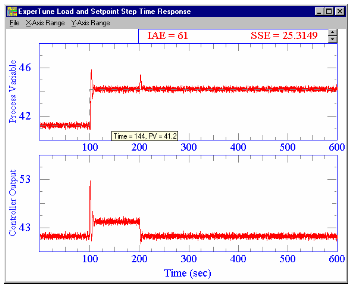
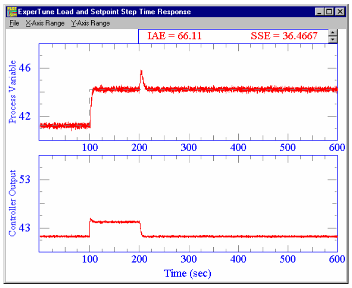
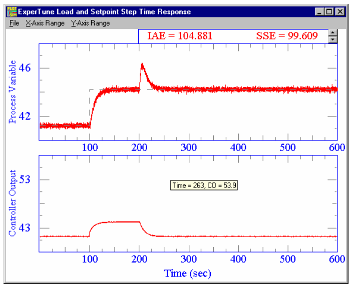
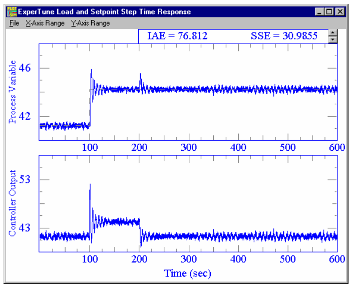
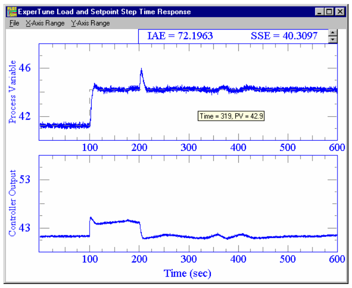
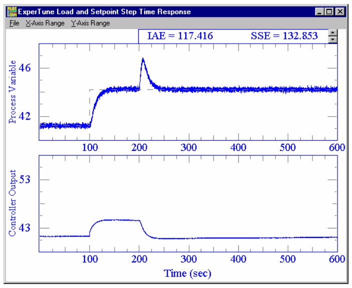
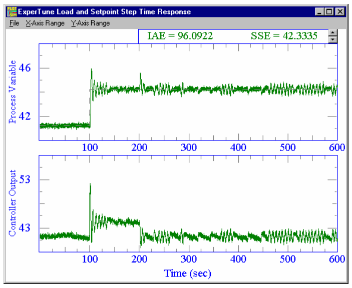
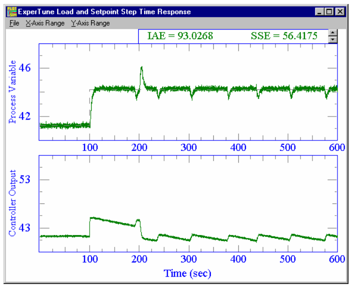
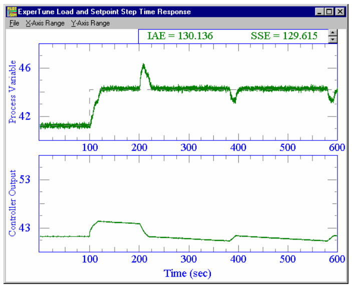
- a perfect valve,
- a valve with 1% hysteresis (backlash=hysteresis),
- a valve with 1% stiction.

For each case, 3 PI controllers (ISA algorithm) were used; in each case ExperTune was used to tune the loop and analyze the data :

- aggressive tuning based on Ziegler/Nichols, K_p=: 2.7, T_i=3 s;
- moderate tuning based, K_p=: 0.84, T_i=2.4 s;
- sluggish tuning based on Lambda tuning, K_p=: 0.28, T_i=3 s;

At 100s, a set-point change of 3 % is applied and at 200s a load change of 3%. Each graphic displays the IAE (integral of absolute error) and SSE (integral of squared error).

Figure 12

Tuning	Aggressive (Ziegler/Nichols)	Moderate	Sluggish (Lambda)
Perfect valve	 ExperTune Load and Setpoint Step Time Response IAE = 61 SSE = 25.3149 Time = 144, PV = 41.2	 ExperTune Load and Setpoint Step Time Response IAE = 66.11 SSE = 36.4667	 ExperTune Load and Setpoint Step Time Response IAE = 104.881 SSE = 99.609 Time = 263, CO = 53.9
Hysteresis=1%	 ExperTune Load and Setpoint Step Time Response IAE = 76.812 SSE = 30.9855	 ExperTune Load and Setpoint Step Time Response IAE = 72.1963 SSE = 40.3097 Time = 319, PV = 42.9	 ExperTune Load and Setpoint Step Time Response IAE = 117.416 SSE = 132.853
Stiction=1%	 ExperTune Load and Setpoint Step Time Response IAE = 96.0922 SSE = 42.3335	 ExperTune Load and Setpoint Step Time Response IAE = 93.0268 SSE = 56.4175	 ExperTune Load and Setpoint Step Time Response IAE = 130.136 SSE = 129.615

Tuning	Aggressive (Ziegler/Nichols)					Moderate					Sluggish (Lambda)				
	Variability (300 to 600s)	Settling time for SP change	Time to remove a disturbance	PV upset after load change	IAE	Variability (300 to 600s)	Settling time for SP change	Time to remove a disturbance	PV upset after load change	IAE	Variability (300 to 600s)	Settling time for SP change	Time to remove a disturbance	PV upset after load change	IAE
	%	s	s	%	%s	%	s	s	%	%s	%	s	s	%	%s
Perfect valve	0.49	16	11	1.3	61	0.45	8	14	1.6	66	0.45	33	40	2.1	105
Hysteresis=1%	0.55	16	11	1.1	77	0.48	18	15	1.6	72	0.45	33	41	2.5	117
Stiction=1%	1.10	21	18	1.1	96	0.80	18	13	1.4	93	1.16	24	28	2.1	130

Conclusions

Finally, to summarize:

- with a perfect valve, more aggressive tuning reduces load change effect;
- aggressive tuning emphasizes valve problems;
- variability at steady state depends mainly on the noise level; variability in real life depends also on the amount of disturbances;
- sluggish tuning reduces valve problems but is slow to remove a disturbance and slow to follow the set-point;
- if hysteresis is present, then the valve will move more but the performances (variability, IAE, SSE) will be slightly affected;
- if stiction is present the variability will increase and cycling will appear;
- moderate tuning represents a good compromise for IAE, speed of response and variability;
- backlash or hysteresis is a problem but stiction is a lot worse; backlash has fewer impacts if sluggish tuning is used.

To reduce stiction

- Select properly the valve and the actuator.
- Maintain your valves regularly.
- Buy a strong actuator and a good positionner.
- Check your valves often while the process is running, especially before a shutdown.

Credit

The graphics were done using ExperTune from ExperTune Inc.

About the author:

Michel is a registered professional engineer, university lecturer, author of several publications and books on instrumentation and control. Michel has 23 years of plant experience including these companies: Monsanto Chemicals, Domtar Paper, Dow Corning and Shell Oil. He is experienced in solving unusual process control problems and he is also a pioneer in the implementation of fuzzy logic in process control.

Michel Ruel P.E., Top Control Inc.

555, Route 78, Swanton, VT, 05488
Tel 1-877-867-6473 Fax 418-834-2651 Email mruel@topcontrol.com

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