Analyze and Optimize Your Processes Through Your HMI

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1: Before You Tune

There is much to be gained by optimizing control loops. This can be done using a software link to a HMI. It has been estimated that 80% of process control loops cause more variability running in automatic mode than in manual. Studies showed that some 30% of all loops oscillate due to non-linearities such as hysteresis, stiction, dead band, and non-linear process gain. Another 30% oscillate because of poor controller tuning.

With a poorly optimized loop, an upset in the direction towards inefficiency results in giving away product. Alternately, a load may cause off-spec product. When a control loop runs optimally, variability is minimized. Better tuning keeps the process on spec and reduces give-away of often expensive ingredients.

However, tuning objectives vary for different types of processes. For example, in a steam header, the pressure has to be maintained at the allowable maximum without large errors so the safety valves will not open. The PID controller must be tuned tightly to ensure the valve that controls the flow from the main header will move quickly to eliminate the effects of disturbances.

On the other hand, the PID controller of a robot arm that manipulates nitro-glycerine vessels has a different objective. The control loop must be optimized to change the setpoint without overshoot or cycling.

Performance Objectives

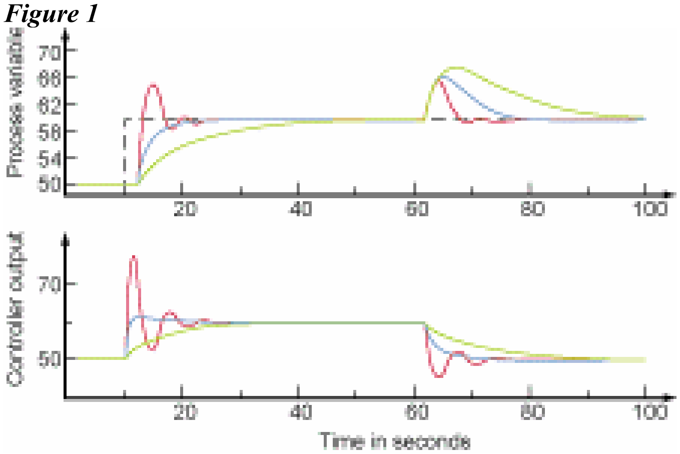
Most engineers and technicians tune process control loops using trial and error, observing the response to setpoint changes. To achieve good setpoint response takes a skilled intuitive understanding of the shape and speed of response. Only experienced people are able to achieve good setpoint response this way.

Unfortunately, once a loop is tuned for good setpoint response, the response to upset is usually very sluggish. Good setpoint tuning does not automatically result in good recovery from upsets. Unfortunately, it is upsets that usually are the source of off-spec product and poor variability.

Modern analysis software can easily be linked to your HMI (using DDE, OPC or a special driver). Using modern tools to analyse a loop will give the engineer or senior technician helpful hints about the process: numbers and graphics will inform the user about design, equipment performance, and interactions with other loops. Modern tools also let the engineer or the technician select appropriate tuning parameters for the control objective. And since the algorithms used in PID controllers are different from one manufacturer to another, in many cases, the algorithm is user selectable.

WHAT DO YOU WANT?

Figure 1



The same loop can be tuned for robustness (green), neutral response (blue) or speed, depending on the objectives

The characteristics of good control are difficult to obtain. When tuning a loop, one must make compromises between robustness and speed of response. Robustness is the ability of the control loop to remain stable when the process (mainly dead time or process gain) changes.

What is good control?

- Good setpoint response without overshoot.
- Good setpoint response with a maximum overshoot.
- Response time matched with another loop so loops will be synchronised.
- Response time long enough to ensure the loop will not react with another loop.
- Load disturbance quickly rejected.
- Load disturbance rejected without cycling.
- Robust tuning so the loop will remain stable when the process changes.
- Aggressive tuning so the error will remain small enough to keep the product in specs.
- Minimum variability.

Usually, to obtain robustness:

- Speed of response is longer.
- Errors are greater when a disturbance occurs, and
- Disturbances are not easily rejected.

Usually, if the response is fast:

- The loop is less robust.
- Errors are small when a disturbance occurs, and
- Disturbances are quickly rejected.

The trends in Figure 1 show the same flow loop tuned for different objectives.

A control loop consists of the process, measurement, controller, usually a current to pneumatic (I/P) transducer, and valve. Optimal process control depends on all of these components working properly. Hence, before tuning a loop, one must verify if each component is operating properly and if the design is appropriate.

Choosing the optimal PID tuning should be done after making sure all of the other components are working properly. The optimal tuning parameters ensure your equipment is used at maximum efficiency.

Questions to Be Answered

The following steps outline a procedure for approaching and optimizing a process control loop. We need to answer the following questions:

1. Process gain: Is the control valve sized properly? Often, valves are oversized. If so, the controller output will be at one end of the range when the loop is in automatic. Also, oversizing the valve will amplify non-linearities such as hysteresis, stiction, different response to small and large changes, and operating near the seat.
The process gain should be between 0.3 and 3. The ideal process gain is 1. A process gain that is too high will not permit the controller to work at its full potential: the controller will have to be tuned with a small proportional gain.

2. Hysteresis/Stiction: Does the control valve have harmful hysteresis and/or stiction? Hysteresis is a difficulty but stiction is really the main problem. Stiction occurs when friction is present.
Hysteresis should be less than 3%, significantly less if the loop is to be tuned tightly. Stiction should be less than 1% and often 1% is too much.

3. Sensor/transmitter: Is the measurement sensor working properly? From your experience, do the numbers make sense? For example, is the dead time small enough? If a transmitter is not properly installed, the dead time can be too long; if a filter is added in the transmitter, the equivalent dead time could be longer.

4. Noise band: Is there an excessive amount of noise in the loop? When disturbances occur too fast to be removed by the PID controller, they are called noise. Filtering may help. The filter should be small enough to not increase the equivalent dead time and large enough to reduce the noise.
Selecting the filter time constant is a trade-off between increasing the equivalent dead time and reducing the amount of noise. When the noise is reduced, the controller output is smoother.

5. Non-linearities: How non-linear is the loop? A loop is non-linear when the process gain varies. All loops are somewhat non-linear. It is the degree of non-linearity that we are interested in. If the loop gain varies by more than a factor of two or three, then linearization will help optimize the loop.
6. Asymmetry: Does the loop respond differently in one direction than in the other? Often, a valve responds more quickly in one direction than the other. Also, in temperature processes using one fluid to add heat and another to remove heat, the two fluids are different and the characteristics of the process are different.
If the equivalent dead time or the equivalent time constant are different depending on the direction, use the worst case to tune the loop or use a special algorithm.

7. Tuning: Is the loop optimally tuned? If the loop is tuned aggressively to minimize error, the robustness is small; if the loop is tuned sluggishly to reduce variability, the recovery time after a disturbance is long.

Tuning parameters are selected to make a compromise between robustness and performance. The loops upstream could interact--selecting the appropriate tuning parameters will allow decoupling. At the opposite, if loops need to be synchronized, selecting the appropriate tuning parameters will ensure they work in accordance.

2: Troubleshooting

Before tuning a PID controller, it is wise to perform a series of tests on the loop to find any conditions that would compromise its performance. Correct these conditions if possible to make the tuning more effective.

The Tests

Testing is performed by collecting data with the controller in automatic mode under normal operating conditions, then introducing a step change. For further diagnosis, data can be collected with the loop in manual mode for comparison.

When collecting data, the scan time must be smaller than or equal to the update time in the controller, and the update time should be smaller than the equivalent dead time of the loop. In many controllers, the update time is user-selectable.

Collected data will show the operating range and performance of the final control element. Is the controller output operating at one end of the range? Is the valve operating near its seat? Does the controller output change by a very small amount? If so, the valve or final control element may need to be resized to give better controller output resolution.

Does the loop cycle? If the loop cycles in automatic but not in manual mode, the cause of the cycle is the closed loop. The cycling may be due to hysteresis, non-linearities, or poor tuning.

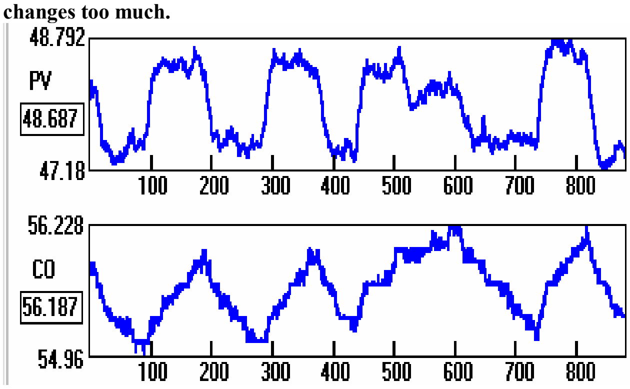
A cycle in a linear loop caused by poor tuning will look sinusoidal.

A sawtooth-shaped cycle can be caused by stiction or by non-linearity.

Figure 2

Stiction (in a flow loop)

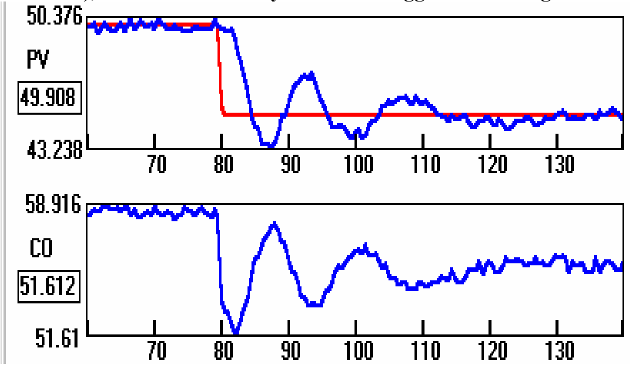
In this process notice how the output is continuously cycling, this is because of stiction: each time the valve moves, the process variable changes too much.



Cycling due to hysteresis usually has a longer period when the process variable is near the setpoint. As the error is reduced, the controller output change is gradually reduced and the effect of hysteresis becomes more important.

Figure 3

Hysteresis Here the loop is cycling after a Setpoint change (period increases), this is because of hysteresis and aggressive tuning.



Loop tuning software can ease the collection, presentation, and interpretation of data.

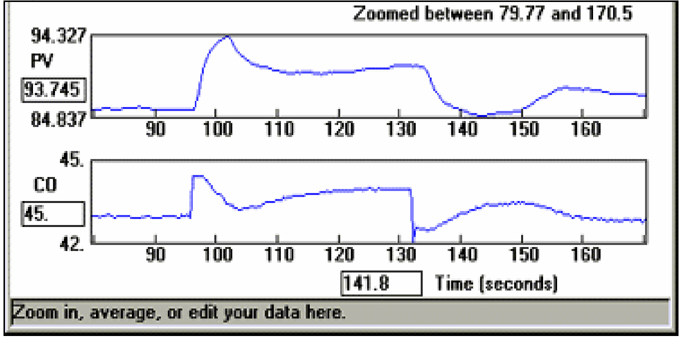
The following example of loop analysis was done using Multi-Loop Tuner from ExperTune, Hubertus, WI.

Sleuth Out Cycling

First, tests were performed on a steam pressure control loop in a paper mill where operators complained about poor performance, cycling, and instability. The loop was taking more than 30 seconds to reach the new value after a setpoint change (Figure 4). This loop could not be shut down.

SETPOINT CHANGE

Figure 4

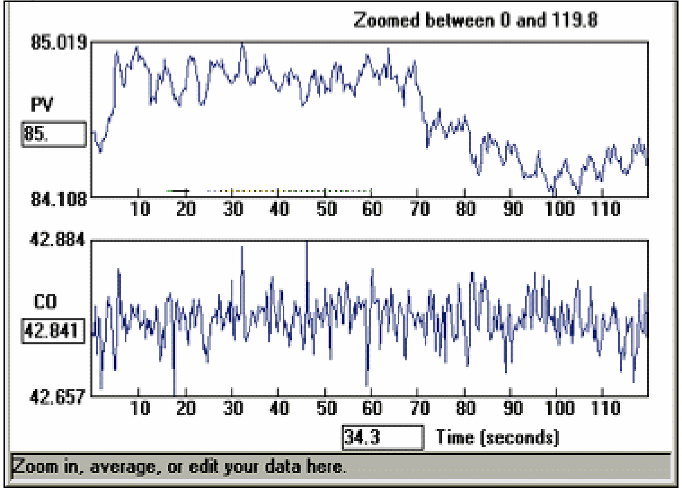


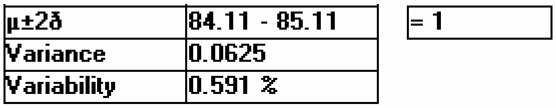
Tests were performed on a steam pressure control loop in a paper mill where operators complained about poor performance, cycling and instability. The loop was taking more than 30 seconds to reach the new value after a setpoint change. This loop could not be shut down

Next, the loop was observed for two minutes in automatic (Figure 5). The variability was 0.59% and oscillations are present at 30 seconds and five seconds. If properly tuned, the loop will handle the 30-second cycling, but the five-second cycling is too fast and must be eliminated at its origin.

CONSTANT SETPOINT

Figure 5



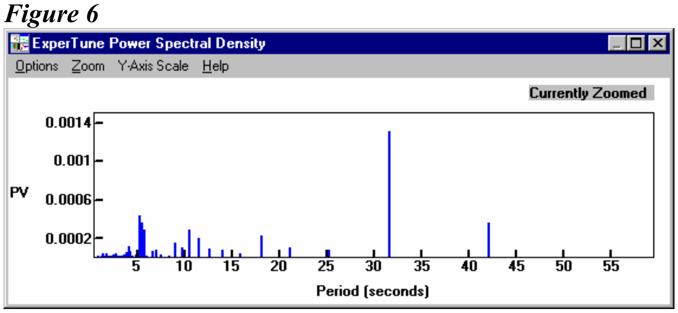


µ±2σ	84.11 - 85.11	= 1
Variance	0.0625	
Variability	0.591 %	

Observing the loop for two minutes in automatic showed that variability was 0.59% and oscillations were present at 30 seconds and five seconds. If properly tuned, the loop will handle the 30-second cycling, but the five-second cycling is too fast and must be eliminated at its origin.

POWER SPECTRAL DENSITY

Figure 6



The power spectral density graph gives the content of the process variable at each frequency. It can reveal hidden cycling from an upstream process control loop or mechanical problems. Oscillations also can be generated by the tuning parameters or periodic load disturbances.

The power spectral density graph gives the content of the process variable at each frequency. These hidden oscillations could be from other loops or generated by the tuning parameters. Cycling can also be due to periodic load disturbances. The power spectral density when done in manual mode reveals also 5 and 30 seconds cycling.

It is important to identify and minimize or eliminate cyclic upsets. Do not expect the controller to remove a cyclic upset caused upstream unless this cycling is slow in comparison with the loop dynamics.
You may need to run power spectral densities on upstream loops, one at a time, moving farther and farther back, until the source of the oscillation is found. Look for a spike in the power spectral density at the same frequency as the oscillation in the loop. A cross-correlation analysis may help to pinpoint the upstream loop you are looking for.

On this steam loop, the five-second cycling was from a relief valve, which was to be checked at the next shutdown. The 30-second cycling might also be from a mechanical problem--the loops in that part of the process were analyzed and tuned, and none of them were implied in that cycling.

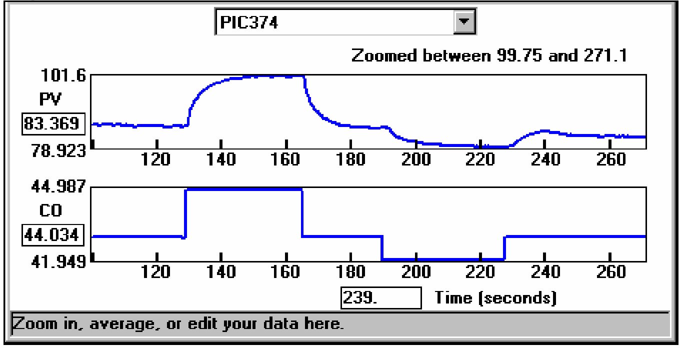
Smooth Out Response

When any cycling in manual mode has been minimized, take a new set of readings in automatic. This step is optional, but can be very useful. Does the controller increase or decrease the performance? Is the variability greater in automatic mode? Does cycling appear in automatic mode (controller tuned too aggressively)?

How noisy is the measurement signal? If the noise is larger than 2-3%, a measurement filter may improve control. Since the derivative action of a PID controller works on the derivative of the signal, any noise in the process is greatly amplified when derivative action is used. A filter may allow you to add derivative to loops, which can significantly improve performance.

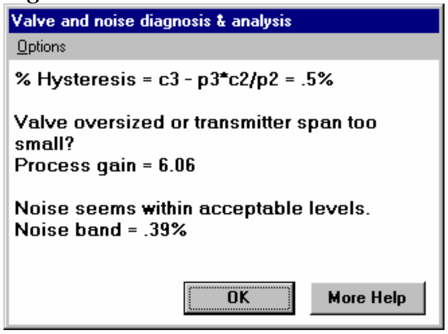
LOOP IN MANUAL

Figure 7



Check the process gain (Figure 8). In this case, the process responds well and noise is small, but the process gain is very high. While the controller output change is 3%, the process variable change is 23%. The process gain is around eight, and this is definitely too high.

Figure 8



% Hysteresis = c3 - p3*c2/p2 = .5%

Valve oversized or transmitter span too small?
Process gain = 6.06

Noise seems within acceptable levels.
Noise band = .39%

To check hysteresis, make two controller output changes in one direction and one step in the other. This valve has little hysteresis, but the process gain is high, so it is easy to observe the hysteresis effect.

In manual mode, check the hysteresis and stiction of the loop. For the hysteresis check, make several controller output changes: two steps in one direction and one step in the other

(Figure 7). Finally, to detect stiction, make a very small fourth step (or a series of steps).

Using the data, run a hysteresis check on the loop. If the hysteresis is more than 1% for valves with positioners and 3% for valves without positioners, you should repair or change equipment. Hysteresis of 1-4% degrades loop performance, while with tight tuning, hysteresis greater than 3% causes oscillations.

The stiction test, a series of small steps (0.5%) in the controller output, shows the amount of change needed before the valve really moves (as indicated by a change in the process variable).

Is It Linear?

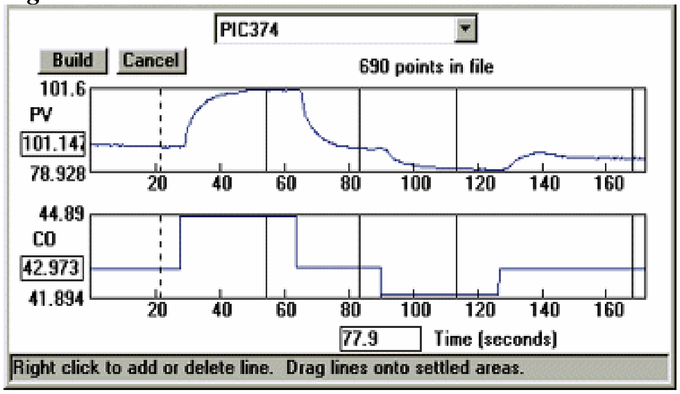
To determine linearity, run the loop in manual or automatic and let it settle at several different locations in the controller output range (Figure 9). If in manual mode, 15% steps starting at 5% work well, for example, at 5%, 20%, 35%, 50%, 65%, 80%, and 95%.

You can run these tests in automatic if both the measurement and output reach a full settled condition after each step. If in automatic mode, the setpoint should be varied from the minimum to the maximum allowable.

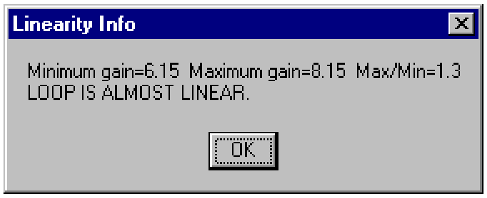
Of course, this step is not always possible. If it must be skipped for process considerations, be careful when tuning the controller. A safety factor is usually applied when selecting the tuning parameters if the behavior of the process is unknown outside the range of previous steps.

LINEARIZATION CHECK

Figure 9



Right click to add or delete line. Drag lines onto settled areas.



Minimum gain=6.15 Maximum gain=8.15 Max/Min=1.3
LOOP IS ALMOST LINEAR.

To determine linearity, let the loop settle at several different locations in the controller output range. If the ratio of the highest to lowest gain is more than three, add (or modify any existing) output characterization.

Graph the process characteristic from the data collected at various settled areas. How linear is the process? Look for the lowest and highest-slope areas. The lowest slope is the lowest gain; the highest is the largest gain. The ratio of the highest gain to lowest gain should be no more than three and preferably less than two.

If the ratio is higher than three, you should add (or modify) any existing output characterization to the loop, which computes X-Y pair values or uses an equation to compensate for gain.

An output characterizer can greatly benefit a split-range control loop. Split-range loops switch between two or more valves depending on the controller output--for example, below 50% output the loop is cooling with chilled water or heat-exchanged oil; above 50% it is heated with steam, hot water, or furnace-heated oil. These loops are usually highly non-linear.

Do not use an output characterizer to linearize pH loops--these require input characterization. With such loops, use gain scheduling based on the process variable or the error.

Check Symmetry

Next, check for asymmetry in manual or automatic mode. Perform step tests in the opposite direction from the last step or, preferably, repeat the steps in the opposite direction. Does the process respond differently in the up direction versus the down?

If so, can you reduce or eliminate the discrepancy? Asymmetry occurs, for example, with a spring and diaphragm valve where the pressure is applied to move the valve in one direction and the spring is used in the other direction.

If you cannot eliminate the asymmetry, you must use the more conservative tuning or special algorithms that tune the controller differently depending on the direction.

Based on the above tests, you may need to do maintenance on the valve, add filtering, linearize the loop, repair or maintain a sensor, or identify and remove upstream cyclic upsets.

3 : How to tune a loop

The Right Approach Can Reduce Variability, Cut Response Time, and Increase Robustness

Tuning control loops for optimal performance is a noble endeavour, and modern loop-tuning software tools make it look easy. But before tuning a loop, it is critical to understand the importance of defining the objectives, understanding the limitations of your equipment, and dealing with loop characteristics.

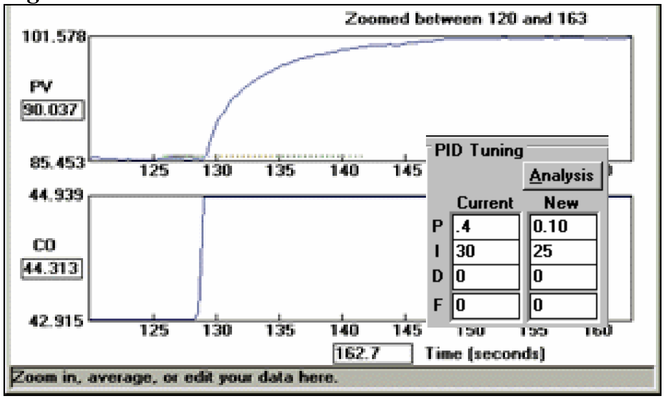
Plant efficiency and consistent product quality depend on proper loop performance, but PID tuning is only the last step.

The last step is to identify the highest-gain, largest-dead time location in the loop and plan to tune for that worst case.

Figure 10 shows the worst case for the paper mill steam pressure control loop example from Part II. Here, the PID controller is part of a DCS system. This DCS uses a parallel algorithm. The software contains a database with more than 200 PID controllers. This database informs the software of the algorithm, units, and special functions.

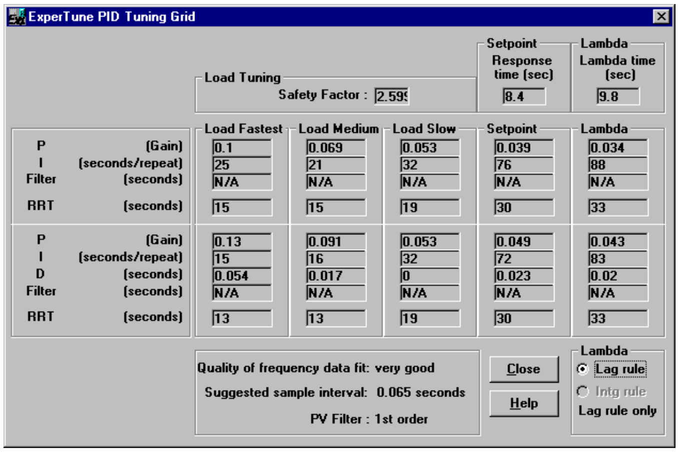
THE WORST CASE

Figure 10



	Current	New
P	.4	0.10
I	30	25
D	0	0
F	0	0

Tune for the highest-gain, largest-dead time location in the loop. Shown is the worst case for a paper mill steam pressure control loop



Load Tuning — Safety Factor : 2.59

Setpoint — Response time (sec): 8.4

Lambda — Lambda time (sec): 9.8

		Load Fastest	Load Medium	Load Slow	Setpoint	Lambda
P	(Gain)	0.1	0.069	0.053	0.039	0.034
I	(seconds/repeat)	25	21	32	76	88
Filter	(seconds)	N/A	N/A	N/A	N/A	N/A
RRT	(seconds)	15	15	19	30	33
P	(Gain)	0.13	0.091	0.053	0.049	0.043
I	(seconds/repeat)	15	16	32	72	83
D	(seconds)	0.054	0.017	0	0.023	0.02
Filter	(seconds)	N/A	N/A	N/A	N/A	N/A
RRT	(seconds)	13	13	19	30	33

Quality of frequency data fit: very good

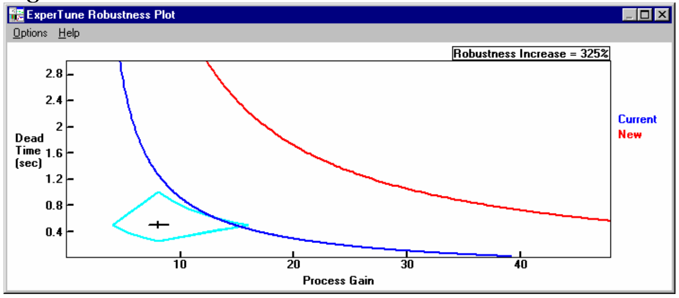
Suggested sample interval: 0.065 seconds

PV Filter : 1st order

Lambda
● Lag rule
○ Intg rule
Lag rule only

SEEK ROBUSTNESS

Figure 11



This robustness plot shows the trade-off between tight Tuning and stability. It can be used to quickly analyze the stability (sensitivity or robustness) of a loop. Here the robustness is 3 times better with new tuning parameters.

When the controller uses a series or an ideal algorithm, it is easy to link the equivalent process deadtime to the integral time and derivative time. However, with a parallel algorithm, the numbers are sometimes quite different from what people expect.

The tuning parameters are chosen, in this case, to ensure robustness. This loop must eliminate disturbances quickly, but the valve has not been tested throughout its range, so a safety factor of 2.6 is used. Also, the valve only operates over a small part of its range and the behaviour of this loop is greatly dependent on the valve.

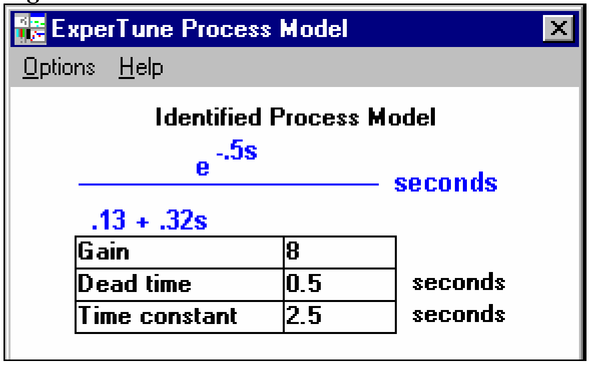
If the loop interacts with others, the parameters must be chosen accordingly: in this case, the other loops are a lot slower and the loop can be tuned fast. If another loop is at the same speed, one of the two loops should be detuned to be sure the speeds are different.

The selected tuning parameters are “Load Fastest”, which gives fast recovery after a disturbance and enough robustness. At the opposite, “Setpoint” tuning (also named Lambda tuning) would be too slow (three times slower) and not aggressive enough. Other applications could use settings between these extremes.

The robustness plot (Figure 11) is an analysis tool. It shows how sensitive (or robust) the loop is to process gain or process deadtime changes. Robustness plots graphically show the trade-off between tight tuning and stability. Use the robustness plot to quickly analyze the stability (sensitivity or robustness) of a loop.
The plot has a region of stability and a region of instability. The solid (red and blue) lines on the robustness plot are the limits of stability. To the right and above the solid lines (higher gain and delay ratios), the closed loop process is unstable. To the left and below the solid lines, the closed loop system is stable. The cross shows the process gain and deadtime at the selected process values.

The software uses a model to predict process behavior (to determine tuning, the software uses real data, not a model).

Figure 12



Identified Process Model

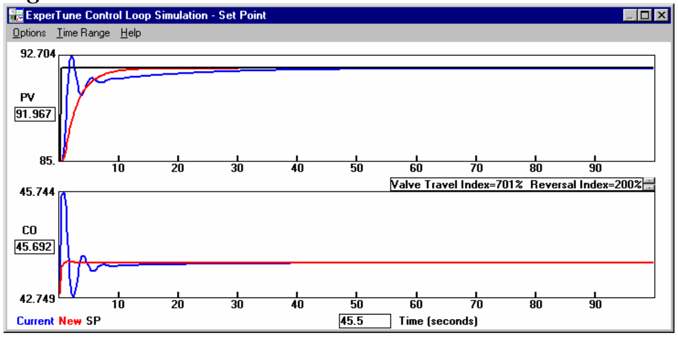
$$\frac{e^{-.5s}}{.13 + .32s}$$ seconds

Gain	8	
Dead time	0.5	seconds
Time constant	2.5	seconds

This model was identified by the program on the frequency response.

Simulation for a setpoint change

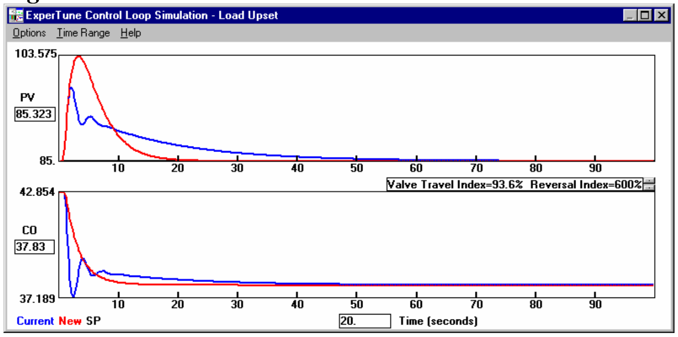
Figure 13



Valve Travel Index=701% Reversal Index=200%

Simulation for a load change

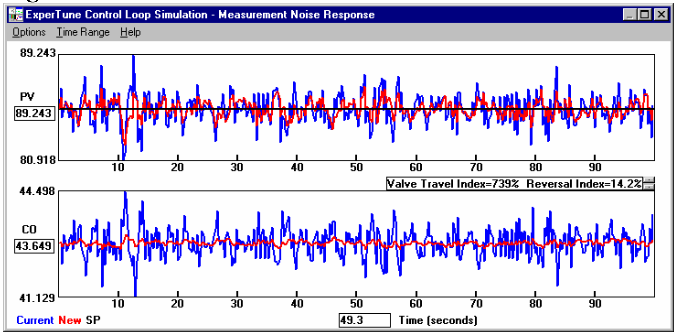
Figure 14



Valve Travel Index=93.6% Reversal Index=600%

Simulation for noise

Figure 15



Valve Travel Index=739% Reversal Index=14.2%

The "Load Fastest" tuning parameters are selected but a safety factor of 2.6 was applied. The robustness is greatly improved (by a factor of 3) and so is the response time (by a factor of 5).

The simulated response corresponds at the actual loop behavior, which guaranties the data validity. The valve travel index predicts the valve movements will be greatly reduced by a factor until 7.

Check It Out

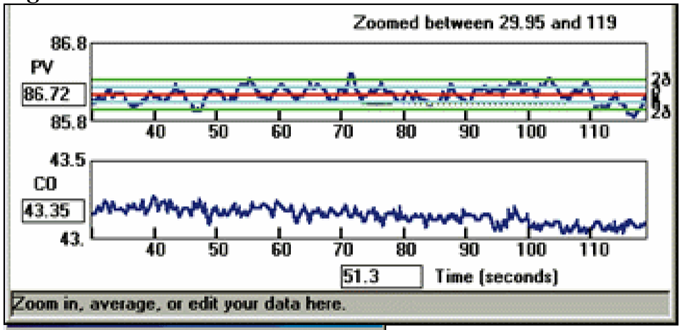
To see how the new tuning parameters affect the loop, compare variability before and after tuning. Collect process variable and controller output data with the controller in automatic at normal operating conditions (Figures 16, 19).

CHECK RESULTS

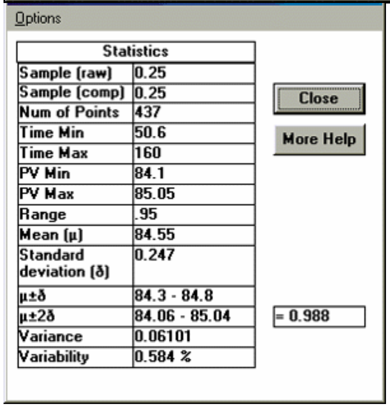
Before

Constant setpoint

Figure 16



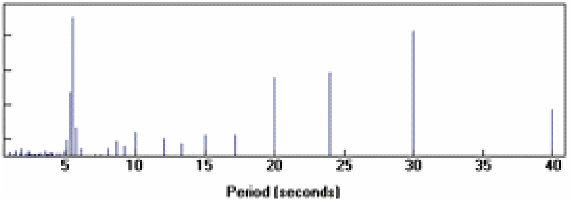
Zoom in, average, or edit your data here.



Statistics	
Sample (raw)	0.25
Sample (comp)	0.25
Num of Points	437
Time Min	50.6
Time Max	160
PV Min	84.1
PV Max	85.05
Range	.95
Mean (μ)	84.55
Standard deviation (δ)	0.247
μ±δ	84.3 - 84.8
μ±2δ	84.06 - 85.04
Variance	0.06101
Variability	0.584 %

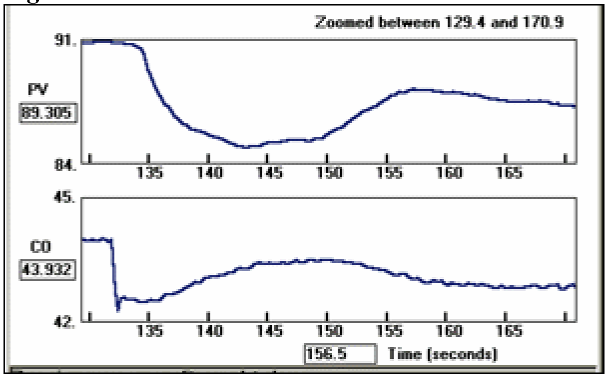
= 0.988

Figure 17



Setpoint change

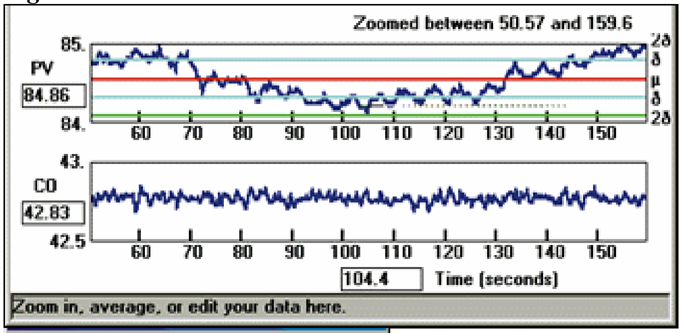
Figure 18



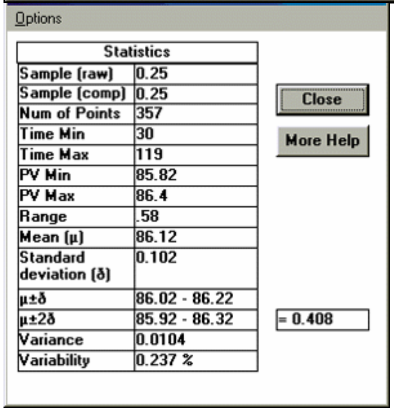
After

Constant setpoint

Figure 19



Zoom in, average, or edit your data here.

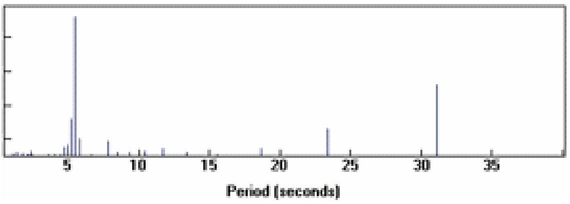


Statistics	
Sample (raw)	0.25
Sample (comp)	0.25
Num of Points	357
Time Min	30
Time Max	119
PV Min	85.82
PV Max	86.4
Range	.58
Mean (μ)	86.12
Standard deviation (δ)	0.102
μ±δ	86.02 - 86.22
μ±2δ	85.92 - 86.32
Variance	0.0104
Variability	0.237 %

= 0.408

Statistical analysis before and after shows variability is cut by half. The short oscillations remain but the long oscillations are removed. This was easily visible on the trends.

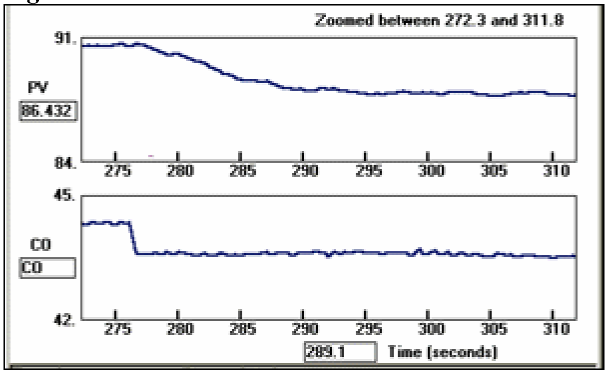
Figure 20



Cycling before (top) and after tuning (bottom) shows great reduction, but cycling from the relief valve remains.

Setpoint change

Figure 21



The response time is a lot smaller, and the valve moves less.

Write the Report

It is a good idea to write a report and insert pictures to help troubleshoot the loop in the future. The tuning package from ExperTune, Hubertus, WI., used for this example, has built-in tools to generate an automated report, including graphics, values computed, and analysis.

The report on this loop also noted that the loop would perform better with a properly sized valve. A hidden cycling of five seconds from a leaking relief valve will disappear after the relief valve is replaced or repaired.

Conclusions

The new tuning parameters increased loop performance:

- Three times more robust.
- Response time reduced by 80%.
- Variability reduced by half.
- Valve movements reduced by 7 .

After three weeks of operation, the paper mill steam pressure control loop was performing very well and the operators no longer complained about poor performance, cycling, and instability.

About the author:

Michel is a registered professional engineer, university lecturer, and author of several publications and books on instrumentation and control. Michel has 22 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. mruel@topcontrol.com

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