Outline

• General Information - Industry Challenges and Opportunities
• Breakdown of Control Loop Performance Methods
• Typical Performance Metrics Related to
  – Controller Response
  – Mechanical Issues
  – Process/Interaction Issues
• Available Tools
  – Case Study Using PlantESP™
General Information
Industry Challenges and Opportunities

- Increased Regulation
  - Governmental bodies legislating higher levels of control through reduced emissions on other production-related waste restrictions
  - Documentation of process performance and adherence to production specifications increasing across the process industries
  - Tighter regulatory controls resulting in higher and more frequent fines for manufacturers

United States national policy to implement Cap-and-Trade program for CO2 emissions

- Increased Costs
- Under-Performing Investments
- Dwindling Resources
“If 30% of the loops are operating inefficiently in automatic, the annual opportunity cost would be $350,000.”

Underperforming Investments

- 70% of PID controllers are typically operating in automatic mode
- 85% of those controllers are operating inefficiently
- 65% of controllers are poorly tuned or de-tuned to mask control-related problems
- 20% of control systems are not properly configured to meet the control system objectives

1 Mark Schneider and Andrea Wirth, “Light at the End of the Tunnel”
General Information
Industry Challenges and Opportunities

Statistics from the U.S. Department of Labor for 2000-2003 shows a 23% decrease in production workers across all segments of the process industries.

Dwindling Resources

- Economic and technological factors demand that plants become increasingly efficient through the use of automation
- The average factory operates PID control loops that number in the 100s
- The time to tune PID controllers ranges from minutes to days depending on the engineer’s experience and the associated loop’s complexity
- Process control has been relegated to reactive maintenance
Energy represents a significant portion of total production cost. At $78 per barrel in July 2007, the cost of crude was 240% higher than January 2004.

Rising Costs

- Volatile energy costs and rising labor costs are hastening the need for increased efficiency
- Increased competition combined with customer demand for quality, speed, product performance and lower costs are putting an ever greater burden on manufacturing
- Products need to be launched faster than ever in order to remain ahead of the competition

1 Mark Schneider and Andrea Wirth, “Light at the End of the Tunnel”
General Information
Industry Challenges and Opportunities

Economic Benefits of Improving Regulatory Control

- Regular tuning of a plant’s PID controllers is proven to dramatically improve process performance and increase overall plant profitability in the following manner:
  - Increase production throughput: 2% - 5%
  - Increase production yield: 5% - 10%
  - Reduce energy consumption: 5% - 15%
  - Reduce production-related defects: 25% - 50%
Breakdown of Control Loop Performance

Methods

Break Techniques Into 3 Categories

Controller Related
- Tuning Issues
- Cannot Track Set-Point
- Running in the Correct Mode

Mechanical Related
- Incorrectly Sized Equipment
- Sticky Valves/Dampers

Process / Interaction
- Throughput Changes
- Outside Influences

It’s the Blame Game!
Review of Performance Metrics

There are over 50 different performance metrics out there, which should you choose?
Review of Performance Metrics

Keep Things Simple and Easy to Understand

cartoon by Heath Robinson  
OXO® Good Grips® Swivel Peeler
Breakdown of Control Loop Performance Methods

Metrics help categorize control loop problems

Controller
- Controller Speed
- Average Absolute Error
- Percent of Time in Normal
- Output Distribution
- Mode Changes
- Output Travel
- Output Reversals
- Mechanical
  - Control Element Health
- Process / Interaction
  - Spectral Analysis
Typical Performance Metrics Related to Controller Response

**Average Absolute Error**

The AAE is a measure of difference between the Set-Point and the Measured Process Variable. The larger the AAE, the further away from the Set-Point we are. Each Loop has a particular constraint (or benchmark).

\[ 1E = \frac{\sum_{i=0}^{n} |SP_i - PV|}{n} \]

AAE is around 10 GPM at 1AM, then slowly increases up to around 15-16 GPM by 10AM. **Control Has Gotten Worse!**
Performance Metrics Related to Controller Response

• AAE – Why Has the Error Increased?
  – Increased Disturbances / Interactions
  – Increased Set-Point Changes
  – Operator Switched Out of Automatic/Cascade Mode
  – Controlling in Different Operating Range (i.e. non-linear)
  – Mechanical Issues
  – Changes to the Historian Exception/Compression Settings
Track Number of **Mode Changes**
Track Percent of **Time in Normal**

4 Mode Changes (or Operator Interventions)
20% of the Time the Controller was operating in Normal (Automatic)

**Performance Metrics Related to Controller Response**

- Controllers are there to maintain process at a desired set-point.
- When controllers are disabled, the process must now rely on the over-burdened operator to maintain targets.
Performance Metrics Related to Controller Response

• Causes for Controller Coming out of *Normal* Mode
  – Poor Controller Tuning (Oscillations, etc.)
  – Operator Behavior
  – Sensors Reading Bad/Inconsistent Values
  – Incorrect “Remote” Set-Point Values
  – Poor Mechanics on Final Control Element leading to high variability
Typical Performance Metrics Related to Controller Response

**Controller Speed**

Measures the damping response of the closed-loop performance of a control loop.

Based upon the Relative Damping Index Method

- Aggressively tuned loops oscillate and cause excessive wear and tear on the final control element.
- Conservatively tuned Control Loops may not recover quickly enough from disturbances.
Detecting the Disturbance Rejection Patterns

1. Collect Process Data

2. Compute the ACF

3. Determine Damping Factor, $\zeta$

WARNING MATH AHEAD
Autocorrelation Function (ACF)

- Box and Jenkins
  - Used the ACF for choosing ARMA model lengths
  - Introduced the relationship to the process transfer function
  - Extracts response patterns

$$r_{yy}(k) = \frac{1}{(N-k)} \sum_{i=1}^{N-k} [(y(i) - \bar{y})(y(i + k) - \bar{y})]$$

- $r_{yy}(k)$ = ACF coefficient at delay $k$
- $N$ = total number of samples
- $k$ = delay between observations in samples
- $\sigma^2$ = variance
- $\bar{y}$ = average of data
Proposed Method for Automating the ACF

- Control based pattern recognition tool
- Second Order Under-Damped Model

\[ Y(s) = \frac{K}{\tau_n^2 s^2 + 2\tau_n \xi s + 1} D(s) \]

- Crop the ACF length to 10 \( \tau_n \)

<table>
<thead>
<tr>
<th>( \xi )</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi &gt; 1 )</td>
<td>Exponential decay (Slow Response)</td>
</tr>
<tr>
<td>( \xi = 1 )</td>
<td>Fastest exponential decay (Fast with No Overshoot)</td>
</tr>
<tr>
<td>( 0 &lt; \xi &lt; 1 )</td>
<td>Oscillations and Exp. Decay (Overshoot)</td>
</tr>
<tr>
<td>( \xi = 0 )</td>
<td>Pure oscillation</td>
</tr>
<tr>
<td>( \xi &lt; 0 )</td>
<td>Unstable, contains positive exponential</td>
</tr>
</tbody>
</table>
Values of Damping Factor Based on Response

- The model parameters, $\tau_n$ and $\zeta$, provide a means to describe the controllers response.

![Graphs showing non-integrating and integrating responses with varying $\zeta$ values.]

Non-Integrating

Integrating
Relative Damping Index (RDI)

- Performance Index based on $\zeta$

$$RDI = \frac{\zeta_{act} - \zeta_{agg}}{\zeta_{slag} - \zeta_{act}}$$

<table>
<thead>
<tr>
<th>RDI Sign</th>
<th>RDI Value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Any</td>
<td>$\zeta$ is in range, Process running well</td>
</tr>
<tr>
<td>-</td>
<td>$&lt;1$</td>
<td>$\zeta$ is out of range, Control action is too aggressive</td>
</tr>
<tr>
<td>-</td>
<td>$&gt;1$</td>
<td>$\zeta$ is out of range, Control action is too sluggish</td>
</tr>
</tbody>
</table>
Typical Performance Metrics Related to Controller Response

Controller Speed

Measures the damping response of the closed-loop performance of a control loop.

Based upon the Relative Damping Index Method

- Aggressively tuned loops oscillate and cause excessive wear and tear on the final control element.
Why Controller Speed Could Change

- Change in Operating State (i.e. Non-Linear Behavior)
- Replacement of Final Control Element / Sensors
- Someone changed the tunings
- Worsening Valve/Damper Dynamics
- VFD Configuration Changes (i.e. Ramp Speed)
Typical Performance Metrics Related to Controller Response

Output Travel

The Output Travel is defined as the total movement in the output signal. The travel gives us insight into how much effort is required on the controller output to maintain control.

\[ CO_{\text{Travel}} = \sum_{i=0}^{n-1} |CO_{i+1} - CO_i| \]

The Valve Moved 0.28% Over 30 Seconds

Or

8 Full Strokes Every Day
Output Travel

The Output Travel is defined as the total movement in the output signal. The travel gives us insight into how much effort is required on the controller output to maintain control.

As the operating range changes, the amount of controller effort required to maintain set-point increases. **Output Travel increases by 40%!!**

\[
CO_{Travel} = \sum_{i=0}^{i=n-1} |CO_{i+1} - CO_i|
\]
Typical Performance Metrics Related to Controller Response

• Why Output Travel Could Increase
  – Non-Linear Processes
  – Controller Going Unstable
  – Final Control Element Mechanical Issues
  – Large Disturbance Pushing the Controller
  – Changes to Data Historian Compression / Exception Values
Typical Performance Metrics Related to Controller Response

Output Reversals

The output reversals give us an idea of how many times the output signal changes direction. A high number of output reversals can lead to wear and tear on the final control element.

\[
Output \ Reversals = \sum_{i=0}^{n-2} \left\{ \begin{array}{ll}
(CO_{i+1} - CO_i)(CO_{i+2} - CO_{i+1}) > 0 & \rightarrow 0 \\
(CO_{i+1} - CO_i)(CO_{i+2} - CO_{i+1}) < 0 & \rightarrow 1
\end{array} \right.
\]

The Valve Changed Direction 3 times
Over 30 Seconds
Or
8640 Times Every Day

Change In Direction
Typical Performance Metrics Related to Controller Response

Output Reversals

The output reversals give us an idea of how many times the output signal changes direction. A high number of output reversals can lead to wear and tear on the final control element.

\[
Output\ Reversals = \sum_{i=0}^{n-2} \left\{ \begin{array}{ll}
(CO_{i+1} - CO_i)(CO_{i+2} - CO_{i+1}) > 0 \rightarrow 0 \\
(CO_{i+1} - CO_i)(CO_{i+2} - CO_{i+1}) < 0 \rightarrow 1
\end{array} \right.
\]

The Output Reversals increased by 20%

Performance Has Started to Degrade
Typical Performance Metrics Related to Controller Response

• Why Output Travel Could Increase?
  – Non-Linear Processes
  – Controller Going Unstable
  – Final Control Element Mechanical Issues
  – Changes to Data Historian Compression / Exception Values
Typical Performance Metrics Related to Controller Response

The output distribution outlines the areas in which the final control element is spending its time. This allows us to understand if the control element is saturated (sitting at the extreme upper or lower operating range).

The Controller Output Spent most of its time fully closed.
Typical Performance MetricsRelated to Controller Response

• What would cause an output to Saturate?
  – Non-Linear Processes
  – Incorrectly Sized Final Control Element
Typical Performance Metrics Related to Controller Response

Valve Health

The mechanical elements associated with moving a valve or damper can wear over time. As these linkages or other parts start to wear down, their ability to consistently move the valve stem or damper degrades.

Too Many Methods To List ...
Many are proprietary and entail “Pattern Recognition” algorithms

For Flow, Temperature and Pressure Look For Saw-Tooth Style Patterns in the Process Data
Typical Performance Metrics Related to Controller Response

• Why Valve Health Decrease?
  – “Slop” in the Linkages
  – Valve Packing too Tight
  – Over Zealous Maintenance Technicians
Typical Performance Metrics Related to Controller Response

Power Spectrum / Spectral Density

- Measures frequency and magnitude of change in a signal
- Especially good for identifying oscillating behavior
- Different signals may have something in common if spectrum peaks coincide
- Think of it as a Disturbance Fingerprint

Too Many Methods To List ...

WARNING
SERIOUS MATH

Power Spectrum (Spectral Density) Clearly Connects Disturbance (D) to PV Behavior

Process Under PI Control

disturbance (D) oscillates at a frequency of 17 minutes.
Power Spectrum Example

Power Spectrum / Spectral Density

- Measures frequency and magnitude of change in a signal
- Especially good for identifying oscillating behavior
- Different signals may have something in common if spectrum peaks coincide
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Level Control Performance

Pressure Control Performance

Temperature Control Performance

Drum

Several Process Units

Furnace
Power Spectrum Example

- Measures frequency and magnitude of change in a signal
- Especially good for identifying oscillating behavior
- Different signals may have something in common if spectrum peaks coincide
- Think of it as a Disturbance Fingerprint

Too Many Methods To List ...

WARNING
SERIOUS MATH

Power Spectrum (Spectral Density) Connects The Temperature, Pressure and Level Controllers at a Frequency of ~ 68 minutes

Spectral Density / Power Spectrum

Temperature
Pressure
Level

Period (minutes)

21 22 23 25 26 28 30 33 35 39 43 48 54 62 73 89 114 158 256 683
Controller Monitoring and Process Optimization

1900 MW Operating Station

- Staff logs into PlantESP and identifies oscillations in a key production area that directly effects the plant’s Heat Rate Index – a key metric of plant profitability.
- PlantESP’s customizable and multi-layered views present the user with information that simplifies the isolation of the specific control loop’s performance data.
- PlantESP’s easy-to-read gauges and trends provide important diagnostics related to Process, Mechanical, and Tuning.
- PlantESP’s analysis clearly indicates issues associated with Controller Speed, Output Travel, and Average Error.
- PlantESP’s recommend retuning the PID control loops as the appropriate corrective action.
The loop is oscillatory and staff perform a modest closed-loop bump-test in the middle of a transition.

Data from the damper is uploaded into Loop-Pro for analysis, modeling, and tuning.

Loop-Pro’s Non-Steady State (NSS) modeling capability permits the user to accurately model the data in spite of its challenging dynamics, and it provides visual confirmation of the model fit.

Loop-Pro’s simulated performance indicates how the controller will perform using various PID configurations.

Descriptive statistics and stability analysis provided by Loop-Pro equip staff with additional information, facilitating the decision-making process and assuring safe and efficient controller performance.
Controller Monitoring and Process Optimization

1900 MW Operating Station
- Loop-Pro’s automated reports provide staff with a valuable record of their analysis and tuning exercise.
- Comparative Before-vs.-After data readily demonstrates the improvement in control and supports the determination of economic gain.
- PlantESP metrics - Average Absolute Error, Output Travel, etc. – provide staff with details of the changes to loop performance.

Before: Meters show poor performance across key indices.
- Overall Loop Health
- Average Absolute Error
- Output Travel
- Output Distribution
- % Time In Normal
- Controller Speed
- FCE Health

After: Performance improved across all KPIs.
- Overall Loop Health
- Average Absolute Error
- Output Travel
- Output Distribution
- % Time In Normal
- Controller Speed
- FCE Health
Controller Monitoring and Process Optimization

1900 MW Operating Station

- PlantESP’s interaction analysis capabilities – a map of loop frequencies – equipped users with the means for evaluating the Power Spectrum of all loops within the plant’s production environment.
- Like a DNA graphic, PlantESP maps the frequencies of all PID control loops and shows dominant frequencies in increasingly bold color.
- Staff review the frequency peaks of the control loop after tuning and note the elimination of an “event” that reoccurred at 3 minute intervals.

Before: Recurring “event” at ~3 minute interval

After: “Event” eliminated after controller tuning
Questions?

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Thank you for participating!

Please remember to tidy up your work area for the next session. We want your feedback! Please complete the session survey!