CONTROLLER PERFORMANCE ASSESSMENT IN SET POINT TRACKING AND REGULATORY CONTROL

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This paper examines factors that influence the minimum variance performance measure of an SISO control loop. It shows a case where set point tracking performance differed from the regulatory performance during normal operation. The conclusion is that performance assessment must use data representative of the control intention. The results also demonstrated how performance during normal operation was influenced by the nature of a disturbance, and that correlations between signals within a control loop indicated the nature of the disturbance. The results suggest that the manipulated variable can be exploited in controller performance assessment.

Keywords: Controller performance, data, disturbance, set point control, regulation.

1. INTRODUCTION

Single-input-single-output control loop performance assessment has become an important technology in process operations. Many approaches are based upon the Harris index (Harris, 1989; Desborough and Harris, 1992). That index compares control loop performance against a minimum variance benchmark. The concept is that the controller error signal should contain no components such as steady offsets or persistent oscillation that are predictable over a time horizon larger than the loop dead time. The state of the art has been reviewed by Qin (1998) and Harris et.al (1999). Commercial implementations of the technology are in use, for instance ProcessDoc (Matrikon Consulting Inc, Edmonton, Alberta), Loop Scout (Honeywell HiSpec Solutions, Thousand Oaks, CA) and AspenWatch (AspenTech, Cambridge, MA).

A disturbance entering a control loop can affect its performance. One way that an external disturbance may be diagnosed is by modeling or inspection of the cross-correlation of the controller error and a suspected disturbance variable (Desborough and Harris, 1993; Kozub and Garcia, 1993; Stanfelj et.al., 1993). However, disturbances originating within the process equipment itself may not be accessible, for instance those caused by an agitator or by a faulty valve positioner. The empirical work presented here used deterministic and random
disturbances in the process equipment to show how the relative amounts of these disturbances influence the performance index. Correlations between the process variable and manipulated variable ($mv$) are presented to aid the diagnosis task.

It is known that minimum variance control may require vigorous action of the manipulated variable and can lead to maintenance problems for actuator. There is thus an incentive to relax the minimum variance requirement. Kozub (1997) and Huang and Shah (1998) discussed the use of a modified performance target termed the user-specified benchmark while Thornhill (1999) demonstrated the use of longer prediction horizons that suit the control intention, as proposed by Desborough and Harris (1992) and Kozub and Garcia, (1993). In this paper the $mv$ movements from the practical trials were examined for their potential utility in controller performance assessment.

## 2. METHODS

### 2.1 Plant experiments

Data sequences were captured from a continuous stirred tank reactor in the Computer Process Control group of the University of Alberta, Department of Chemical and Materials Engineering. The process schematic is shown at the end of the paper (Fig 5). Computer control of the process was achieved using Simulink and Real Time Toolbox of MATLAB (The Mathworks, Natick, MA) interfaced with the plant. Actuator demands calculated within Simulink were sent to the plant as 4-20 mA signals, and 4-20 mA signals from the instruments on the plant were sent to Simulink for calculation of control actions. A cascade configuration onto cold water flow was implemented for level control, as shown in Fig 5, and temperature control used proportional plus integral control of the steam valve. A benefit of the configuration is its flexible access to the plant inputs. For instance, it was possible to add a known disturbance to the output of the controller so that the valve received a signal comprising the controller demand plus a disturbance. A real process disturbances could be applied by bubbling compressed air through the vessel.

Step tests numbered 1 to 8 (see Table 1) were applied to the plant for assessment of set point tracking. Data sequences from normal operation with a steady set point were also captured.

### 2.2 Collection of disturbance sequences

Fig 1 shows portions of some disturbance sequences captured from the pilot plant using open loop testing. Fig 1(a) is the random noise component appearing on a steady level signal when compressed air bubbles were blown into the tank. Fig 1(b) is the variation in the cold water flow measurement when the valve demand signal was held constant.

![Disturbance sequences captured from plant](image)

**Fig. 1.** Disturbance sequences captured from plant (a) level disturbance from compressed air bubbles (b) cold water flow disturbance.

### 2.3 Simulation

A simulation was created that used heat and mass balance together with valve, instrument and heat data sets. Direct $min$ var. calculation $Pl$ during step $Pl$ in normal operation st. dev of $Δmv/ mA$

<table>
<thead>
<tr>
<th>Data sets</th>
<th>Direct min var. calculation</th>
<th>$Pl$ during step</th>
<th>$Pl$ in normal operation</th>
<th>st. dev of $Δmv/mA$</th>
</tr>
</thead>
<tbody>
<tr>
<td>level loop with various</td>
<td>1</td>
<td>0.20</td>
<td>0.23</td>
<td>0.20</td>
</tr>
<tr>
<td>controller tuning settings</td>
<td>2</td>
<td>0.19</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.18</td>
<td>0.21</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.09</td>
<td>0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>temperature loop with</td>
<td>5</td>
<td>0.74</td>
<td>0.76</td>
<td>0.98</td>
</tr>
<tr>
<td>various controller tuning settings</td>
<td>6</td>
<td>0.47</td>
<td>0.52</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.61</td>
<td>0.67</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.34</td>
<td>0.41</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 1. Summary of performance results from runs using the pilot plant
transfer characteristics measured during calibration of the plant. Noise in the simulation was provided as sequences of the real noise collected during open loop testing of the plant.

2.4 Disturbance testing

Test sequences 9 and 10 described in Table 2 were applied to the plant for 500s. The reason why the flow disturbance sequence was amplified for test 10 is so that its effects would dominate the natural process disturbance. All the disturbance tests used the same controller tuning settings.

Sequences 11 to 13 were applied to the simulation and run for 2000s. In that case there was no natural process noise and the flow disturbance was applied without amplification.

2.5 Data analysis

Controller performance was assessed for tests 1 to 8 for 2000 samples from normal operation using the method given in Desborough and Harris, (1992). Here PI is defined as \( \left( \frac{\sigma^2_{mv}}{\sigma^2_e} \right) \) where \( \sigma^2_{mv} \) is the estimated minimum variance and \( \sigma^2_e \) is the variance of the controller error. Therefore \( PI = 1 \) indicates the loop has achieved minimum variance. The PI calculation requires loop dead times. The level and temperature loop dead times were 2s and 8s respectively.

For the step changes the PI was computed using data sets starting 50s before the step and continuing for 250s after the step, a total of 301 samples. The minimum variance benchmark for tracking performance following the step change in set point was also calculated directly as the ratio between the square of the error between the instant of the step (\( T_{step} \)) and the loop dead time (\( T_d \)), and the square of the total error:

\[
\frac{T_{step} + T_d}{\int_{t=T_{step}}^{\infty} (sp - pv)^2 \, dt} = \int_{t=T_{step}}^{\infty} (sp - pv)^2 \, dt
\]

Movements in the manipulated variable and in the process variable were calculated as:

\[ \Delta mv(i) = mv(i+1) - mv(i) \]

and

\[ \Delta pv(i) = pv(i+1) - pv(i) \]

Correlation coefficients were calculated to determine the static relationships between signals within the loop.

3. RESULTS

3.1 Plant experiments

There were four plant set point tracking tests (step tests) for various controller tuning settings of the level-flow cascade control loop and four for the temperature loop. Fig 2 shows tests 1, 4, 5 and 8. PI results are in Table 1 together with the directly-calculated minimum variance measure and the standard deviations of the mv movements during normal operation.

Fig 3(a) shows the PI results for step tests from Table 1. The closeness of the results to the unit gradient line shows that direct calculation of the minimum variance benchmark and the PI during the step change gave almost the same estimate of the minimum variance performance index for a set point change. Fig 3(b), however, shows that PI for the steps response was not related to the PI during normal operation especially for the temperature loop. The conclusion is that the PI during normal operation is sensitive to some other aspect of loop performance. The next section shows that the explanation for this finding is that the performance of a control loop is influenced by the nature of the process disturbance.

Table 1 shows that the manipulated variable movements during normal operation were related to the PI for set point tracking. Movement was reduced in loops having poor set point performance (tests 4 and 8) and was increased when the loop had better set point performance (test 5). Therefore a loop having minimum variance set point tracking control demands more actuator movement.

The mv movement was not, however, related to the PI during normal operation. Tests 5 and 6 show that the manipulated variable movement could be reduced without much change to the PI for normal operation. Therefore for cases in which actuator wear is a concern there is a need for an enhanced performance measure that pays attention to mv movements, much as mv movements are included in LQG controller design.

<table>
<thead>
<tr>
<th>Test description</th>
<th>Disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. Compressed air bubbled through tank</td>
<td>real</td>
</tr>
<tr>
<td>10. Flow disturbance x10 added to CW valve demand</td>
<td>1(b)</td>
</tr>
<tr>
<td>11. Bubble noise added as disturbance to level in simulation</td>
<td>1(a)</td>
</tr>
<tr>
<td>12. Flow disturbance added to CW valve demand in simulation</td>
<td>1(b)</td>
</tr>
<tr>
<td>13. 11 and 12 in various combinations</td>
<td>1(a) and 1(b)</td>
</tr>
</tbody>
</table>

Table 2. Description of disturbance runs on the pilot plant and in simulation
3.2 Disturbances

The following analysis explores the behaviour of the performance index and other quantities when the disturbances shown in Fig 1 were applied to the plant. In particular, it would be desirable to determine the nature of the disturbance. Table 3 shows the performance indexes from normal operation and correlation coefficients for the plant and simulated runs. Observations are:

- The performance index depended upon the nature of the disturbance.
- There was a high correlation between the dominant disturbance and the \(pv\).
- The correlation of \(\Delta pv\) with \(pv\) and \(\Delta pv\) with \(mv\) depended on the nature of the disturbance.

3.3 Discussion

The first of the above observations is presented graphically in Fig 4(a). It shows that runs dominated by deterministic flow disturbance had a low PI while those dominated by the random bubble disturbance had a high PI. Intermediate cases had intermediate performance. This observation explains the results of the previous section in which performance for step tests was unrelated to performance during routine operation. It also highlights the need for a performance monitoring strategy that uses data representative of the purpose of the loop, as discussed by Eriksson and Isaaacsson (1994).

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There was good correlation between the dominant disturbance and the process variable (columns 4 and 5) although the correlation was not perfect because of the loop dynamics. For instance, first order lag dynamics introduce a phase shift and there may be other noise present. The finding nevertheless implies that the nature of a disturbance that is not well controlled may be inferred from the \(pv\). The idea is related to the cross-correlation method for diagnosis of a disturbance discussed in section 1.

Fig 2. Plant step tests for the level control loop (1 and 4) and temperature loop (5 and 8).

![Fig 2](image)

![Fig 3](image)

![Table 3](image)

Table 3. PI and correlation coefficients for pilot plant and simulated runs with disturbances

<table>
<thead>
<tr>
<th>description</th>
<th>(PI)</th>
<th>(\Delta pv) and (pv)</th>
<th>(\Delta pv) and (mv)</th>
<th>(pv) and (pv) and flow noise</th>
<th>(pv) and flow noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated runs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bubbles only</td>
<td>0.93</td>
<td>-0.65</td>
<td>0.03</td>
<td>0.96</td>
<td>-</td>
</tr>
<tr>
<td>bubble dominated</td>
<td>0.91</td>
<td>-0.57</td>
<td>0.05</td>
<td>0.90</td>
<td>0.03</td>
</tr>
<tr>
<td>equal effects</td>
<td>0.62</td>
<td>-0.39</td>
<td>0.15</td>
<td>0.60</td>
<td>0.38</td>
</tr>
<tr>
<td>flow noise dominated</td>
<td>0.12</td>
<td>-0.20</td>
<td>0.38</td>
<td>0.25</td>
<td>0.59</td>
</tr>
<tr>
<td>Flow noise only</td>
<td>0.002</td>
<td>-0.085</td>
<td>0.99</td>
<td>-</td>
<td>0.70</td>
</tr>
<tr>
<td>Pilot plant runs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bubble disturbance</td>
<td>0.85</td>
<td>-0.64</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flow noise disturbance</td>
<td>0.03</td>
<td>-0.11</td>
<td>0.76</td>
<td>-</td>
<td>0.76</td>
</tr>
<tr>
<td>Test 2 from table 1</td>
<td>0.30</td>
<td>-0.23</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig 3. PI results for set point tracking during step testing and during normal operation. (●) cascade level loop 1 to 4 (■) temperature loop.

![Fig 3](image)
The correlations of $\Delta pv$ with $pv$ and with $mv$ also gave a signature for the disturbance, see Fig 4(b). Cases with random disturbance appeared on the lower left side of the plot, deterministic cases were in the right hand top corner. The explanation of the trend is explored in the Analysis section below. Also shown in Fig 4(b) are the points for the plant runs, test 9 with bubbles present on the left and test 10 with deterministic flow noise disturbance on the right. The conclusion from this section is that the disturbances in the plant runs have been correctly diagnosed.

Test 2 from the previous section had the same controller tuning settings as the tests used to construct the curve. It also lay on the curve and was diagnosed as having some deterministic disturbance but not as much as in test 10. This is correct, the loop was subject to the natural cold water flow disturbance. Results for tests 4 and 8 which have different tuning settings were found not to lie on the curve. Therefore it may be the case that each loop would require its own curve for an application of plots like 4(b) in on-line monitoring of disturbance.

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3.4 Analysis

The correlation of $\Delta pv$ with $pv$ and $mv$ in cases with random or deterministic disturbances can be explained. Recall the finding that the disturbance appearing at the $pv$ is correlated with the true disturbance. That means the $pv$ has a random component if the disturbance is random. A feature of a random sequence $n(i)$ is that the correlation coefficient between its values and the differences $n(i+1)-n(i)$ is $-1/\sqrt{2}$. Therefore it is to be expected that random fluctuations in the $pv$ will show a negative correlation between $\Delta pv$ and $pv$ with a magnitude of up to 0.71 (-0.65 was observed).

For a deterministic periodic disturbance there should be little correlation between $\Delta pv$ and $pv$. Such a disturbance is characterized by smooth movements in which zero crossings happen when the derivative is maximum and extreme values are turning points where the derivative is zero. Therefore the $pv$ and the incremental $\Delta pv$ sequences tend to be orthogonal and their correlation is low.

The reason why $\Delta pv$ correlated with $mv$ in the deterministic case is because of the integral action of the controller. The $pv$ varies with a well characterized frequency of oscillation. Therefore the time trend of its integral and differential are similar apart from a negative sign. Thus the correlation of $mv$ with $\Delta pv$ is strong in the case of the deterministic flow disturbance signal. It is not true, however, that the time trend of the integral and differential are similar when $pv$ contains a random signal and therefore no correlation of $\Delta pv$ with $mv$ is seen when the disturbance is random.

4. CONCLUSIONS

The paper has used plant experimentation and simulation to demonstrate practical issues arising in the interpretation of the control loop performance index ($PI$) of the type described by Harris (1989) and Desborough and Harris (1992). These are the main conclusions:

- Direct calculation of the minimum variance benchmark gave the same result as $PI$ calculation for tracking of the set point during a step change.

- The $PI$ for set point tracking during a step test was not a good predictor of the $PI$ during normal operation. A loop can have poor set point step response but good performance during normal operation. Therefore the purpose of the control loop must guide the test performed.

- The $PI$ during normal operation depended on the nature of the disturbance. For given controller tuning settings the $PI$ was low if the disturbance was deterministic and high if the disturbance was random.
• Correlations between variables in the loop gave a signature that distinguished a random from a deterministic disturbance.
• The nature of the disturbances in two plant runs were correctly identified using the correlation signature.
• A performance index that takes account of movements in the manipulated variable is needed for cases where actuator wear is an issue.

5. REFERENCES


Kozub, D.J. and C.E. Garcia (1993), Monitoring and diagnosis of automated controllers in the chemical process industries, AIChe Meeting, St Louis.

6. ACKNOWLEDGEMENTS

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Figure 5. Plant schematic