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INDUSTRIAL APPLICATIONS OF AUTOMATIC PERFORMANCE MONITORING TOOLS

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Abstract: This paper describes two procedures for automatic monitoring of control loop performance. The first is a procedure for detecting oscillations in control loops, and the second a procedure for detecting sluggish control loops. The focus of the paper is the industrial application of the procedures, and the various implementations possible and available.

1. INTRODUCTION

Many control loops in process control plants perform poorly. The reasons may be equipment problems such as sensor faults or stiction in control valves, or bad controller tuning. There is an increasing understanding of the fact that badly performing control loops cause losses in production as well as quality. See, e.g., (Bialkowski (1993)) and (Ender (1993)). Therefore, there is an industrial interest in performance monitoring tools that detect and make operators and maintenance staff aware of badly performing control loops.

There is also an increasing interest in off-line procedures and plant auditing. The Harris index, see (Desborough and Harris (1992)), has received lots of attention. In this method, the control loop performance is compared with an "optimal" performance, where optimal in this case means minimum-variance control. The Harris index and modifications of it have been applied in the pulp and paper industry, see e.g. (Perrier and Roche (1992)), (Lynch and Dumont (1996)), and (Owen *et al.* (1996)). It has also been applied in the chemical industry, see e.g. (Stanfelj *et al.* (1993)) and (Thornhill *et al.* (1996)). Conclusions about the control loop performance can also be deduced from spectral analysis. Examples are given in (Desborough and Harris (1992)) and (Tyler and Morari (1996)).

There are several reasons for bad control loop performance. One reason is stiction in the control valve, see (Bialkowski (1993)). This results in stick-slip motion and oscillations. These oscillations can be detected by methods like the one presented in (Hägglund (1995)). Another important reason is improper controller tuning. Most control loops in the process industry are conservatively tuned, resulting in sluggish responses to load disturbances, and therefore unnecessarily large and long deviations from the set point. This way of operating the process plants results in decreased product quality.

Why are the controllers conservatively tuned? The main reason is lack of time. The engineers tune the controllers until they are considered "good enough". They do not have the time to optimize the control. Many controllers are tuned once they are installed, and then never again. To retain stability when operating conditions change in non-linear plants, the controllers are tuned for the "worst case". A better solution would, of course, be to use gain scheduling and perhaps adaptation. When a controller is retuned, it is mostly because the process conditions cause oscillatory control. In other words, when the controllers are retuned, they are detuned. When the process conditions change to sluggish control, the controller is normally not retuned again. Sluggish control loops can be detected by the method presented in (Hägglund (1999)).

This paper will first shortly review the two monitoring procedures for detecting oscillating loops and sluggish loops, respectively. These procedures can be implemented in several ways, on line or off line, in the controller or DCS system that performs the control or in an external computer. The advantages and disadvantages of these implementations are discussed and examples from industrial applications are given.

2. MONITORING TOOLS

This section gives a summary of the two monitoring tools.

2.1 *Oscillation detection*

There are several reasons for oscillations in control loops. They may be caused by too high controller gains or oscillating load disturbances, but the most common reason for oscillations is friction in the valve. A procedure for detecting oscillations in control loops was presented in (Hägglund (1995)).

The principle behind the detection procedure is to study the magnitude of the integrated absolute error (IAE) between successive zero crossings of the control error, i.e.,

$$IAE = \int_{t_{i-1}}^{t_i} |e(t)| dt, \tag{1}$$

where t_{i-1} and t_i are two consecutive instances of zero crossings. It is assumed that the controller has integral action, so that the average control error is zero. If no integral action is present, the average value of the measurement signal can be obtained using a low-pass filter.

During periods of good control, the magnitude of the control error is small, and the times between the zero crossings are relatively short. This means that during good control, the IAE calculated according to Equation (1) becomes small. When a load disturbance occurs, the magnitude of $e(t)$ increases, and a relatively long period without zero crossings occurs. This means that the IAE becomes large. When the IAE exceeds a certain limit, IAE_{lim}, it is therefore likely that a load disturbance has occurred.

The underlying idea of the oscillation-detection procedure is to conclude that an oscillation is present if the rate of load-disturbance detections becomes high. The behaviour of the control performance is monitored over a supervision time T_{sup}. If the number of detected load disturbances exceeds a certain limit, n_{lim}, during this time, it can be concluded that an oscillation is present.

The oscillation detection procedure has three parameters that must be set: IAE_{lim}, T_{sup}, and n_{lim}. In (Hägglund (1995)), the value of n_{lim} is set to $n_{lim} = 10$. The supervision time should be proportional to the time constant of the loop. In (Hägglund (1995)) it is suggested to set $T_{sup} = 5 n_{lim} T_u$, where T_u is the ultimate period obtained from a relay autotuning experiment. If such an experiment is not performed, it is suggested to replace T_u with the integral time T_i. Finally, the parameter IAE_{lim} is set to $IAE_{lim} = 2a/\omega_u$, where a as the lower limit of the acceptable oscillation amplitude at the ultimate frequency ω_u. A suggested value of a is 1% of the signal range. Again, if ω_u is not available, it is replaced by $\omega_i = 2\pi/T_i$.

For on-line applications, it is more convenient to perform the calculations recursively. Such a procedure is summarized in the following program:

```
INITIALIZATION
a = 1 [%]
n_lim = 10
if ultimate_frequency is available then
begin
  iae_lim = 2 * a / omega_u;
  t_sup = 5 * n_lim * t_u;
end else
begin
  iae_lim = 2 * a / omega_i;
  t_sup = 5 * n_lim * t_i;
end;
gamma = 1 - h / t_sup;

LOAD DETECTION
if sign(e) = sign(e_old) then
begin
  iae = iae + abs(e) * h;
  load = 0;
end else
begin
  if iae > iae_lim then load = 1
    else load = 0;
  iae = abs(e) * h;
end;

OSCILLATION DETECTION
x = gamma * x + load;
if x > n_lim then
begin
  oscillation = true;
  x = 0;
end;
```

The factor γ determines the time horizon in the filter. Its relation to the supervision time is

$$\gamma = 1 - \frac{h}{T_{\text{sup}}} \tag{2}$$

2.2 *The Idle index*

Many control loops are conservatively tuned, resulting in sluggish control. Figure 1 shows two responses to load disturbances in form of step changes at the process input. One response is good, with a quick recovery without any overshoot. The second response, however, is very sluggish.

Both responses have an initial phase where the two signals go in opposite directions, i.e. $\Delta u \Delta y < 0$, where Δu and Δy are the increments of the two signals. What characterizes the sluggish response is, that after this initial phase there is a very long time period where the correlation between the two signal increments is positive. This observation forms the base for the Idle index, see (Hägglund (1999)), which expresses the relation between the times of positive and negative correlation between the signal increments.

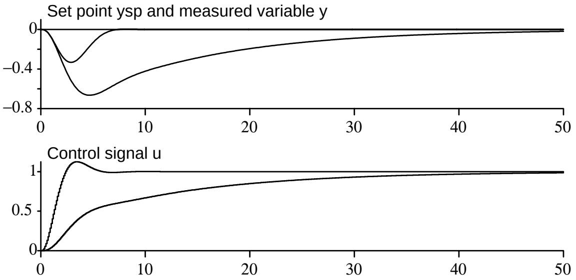

Fig. 1 Good and bad control of load disturbances

From now on, it is assumed that the sign of the static process gain is known, and for simplicity that it is positive. Further, it is assumed that the control loop is subjected to load disturbances only. If there are setpoint changes present, these responses should be excluded from the analysis.

To form the Idle index, the time periods when the correlations between the signal increments are positive and negative, respectively, are first calculated. The following procedures are updated every sampling instant

$$t_{\text{pos}} = \begin{cases} t_{\text{pos}} + h & \text{if } \Delta u \Delta y > 0 \\ t_{\text{pos}} & \text{if } \Delta u \Delta y \leq 0 \end{cases}$$

$$t_{\text{neg}} = \begin{cases} t_{\text{neg}} + h & \text{if } \Delta u \Delta y < 0 \\ t_{\text{neg}} & \text{if } \Delta u \Delta y \geq 0 \end{cases}$$

where h is the sampling period. The idle index I_i is then defined as

$$I_i = \frac{t_{\text{pos}} - t_{\text{neg}}}{t_{\text{pos}} + t_{\text{neg}}} \tag{3}$$

Note that I_i is bounded to the interval $[-1, 1]$. A positive value of I_i close to 1 means that the control is sluggish. The Idle index for the sluggish response in Figure 1 is $I_i = 0.82$. A negative value of I_i close to -1 may be obtained in a well-tuned control loop. The Idle index for the good response in Figure 1 is $I_i = -0.63$. However, negative Idle indices close to -1 are also obtained in oscillatory control loops. Therefore, it is desirable to combine the Idle index calculation with an oscillation detection procedure in order to detect these systems. Idle indices close to zero indicate that the controller tuning is reasonably good.

The conclusions are drawn under the assumption that the load disturbances are step changes or at least abrupt changes. This is a reasonable assumption in many situations, since load changes are often caused by sudden changes in production. However, if the load disturbances are varying slowly, the Idle index may become positive and close to one even in situations when the control is not sluggish. To avoid this, it might be advantageous to calculate the Idle index only during periods when there are abrupt load changes. This can be accomplished using load detection procedures, see (Hägglund and Åström (2000)).

A recursive version of the Idle index calculation is given by the following procedure, which is updated every sampling instant.

$$\begin{aligned} &\text{if } \Delta u \Delta y > 0 \text{ then } s = 1 \\ &\quad \text{else if } \Delta u \Delta y < 0 \text{ then } s = -1 \\ &\quad \text{else } s = 0; \\ &\text{if } s \neq 0 \text{ then } I_i = \gamma I_i + (1-\gamma)s; \end{aligned} \tag{4}$$

Factor γ is defined in Equation (2), where the supervision time is $T_{\text{sup}} = t_{\text{pos}} + t_{\text{neg}}$.

The procedure is sensitive to noise, since increments of the signals are studied. It is therefore important to filter the signals. To do this, it is necessary to have some information about the process dynamics to find a suitable filter-time constant.

It is also desirable to avoid calculations near steady-state, when the signal-to-noise ratio is small. A natural way to ensure this is to perform the calculations only when

$$|e| > e_0 \tag{5}$$

where e is the control error, and e_0 is a threshold based on a noise-level estimate or fixed to a few percent of the signal range.

The supervision time $T_{\text{sup}} = t_{\text{pos}} + t_{\text{neg}}$ used in Eq. (3) or the corresponding factor γ used in the recursive calculations, Eq. (4), must be determined. As for the oscillation detection procedure It is reasonable to determine it as a factor times T_u if this time is available, otherwise as a factor times T_i.

3. IMPLEMENTED WHERE?

The performance monitoring tools may be implemented either in the control system that performs the control, now for simplicity called the DCS (Distributed Control System), or in an external computer system. The advantages and disadvantages of these two approaches are discussed in this section.

3.1 *Operating conditions*

It is important that the monitoring is performed only during normal operating conditions. Data obtained during manual control, during periods when the controller is running in tracking mode, or during periods when the signals are saturated should, e.g., be excluded. The information about these different states of operation are available in the DCS system, but normally not transferred to the external computer systems.

3.2 *Signals available*

The oscillation detection procedure requires that the measurement signal is available. It is advantageous if the setpoint is available, but it is not necessary. However, in the Idle index tool, it is important to exclude excitations caused by set-point changes. Therefore, the setpoint must also be available. This is often not the case in external computer systems. The Idle index tool also requires that the control signal is available. Control signals are often not recorded and often not even possible to record in external computers, since they often are internal signals in the DCS system.

The measurement signal that enters the control block in the DCS system is not the same as the signal that is recorded in an external computer. The same is true for the control signal. First of all, there might be filters and other functions inside the DCS system that alters the signals between the AD/DA converters and the control block. There may also be disturbances added to the signals before they enter the external computer. Finally, the signals are often sampled with different sampling rates.

To summarize, the DCS system has all signals available that are needed. For many control loops, the signals available in the external computer are not sufficient.

3.3 *Parameters available*

There are several parameters in the DCS systems that are useful in the monitoring tools. These parameters are normally not transferred to external computers. The integral time, e.g., is often the only parameter available that describes the time constant of the loop. Such a time is needed to determine the supervision time both in the oscillation detection procedure and in the Idle index calculation. It is also needed to determine suitable time constants in filters. This is of special importance in the Idle index calculations.

The signal ranges are also useful parameters. The signal range of the measurement signal is, e.g., needed to determine the amplitude a leading to IAE_{lim} in the oscillation detection procedure. It is also useful for determination of the threshold e_0 in the Idle index calculation, see Equation (5). The signal ranges are also used to determine when signals become saturated.

3.4 *Programming environment*

The programming environment is often excellent in the external computers, with possibilities to use high-level programming languages, Matlab tools etc. The computational power and speed is often high and the memory admits storage of rather large data sets.

The programming environment in the DCS system is often poor. In some DCS systems, the programming has to be performed using the standard blocks available. Some modern DCS systems have free-programmable blocks, which means that the user can specify the function of a block using a rather convenient programming language. Some DCS systems have the supervisory functions already available as standard blocks.

The computational power and speed is often low in the DCS systems, because of all the other functions already running on the computer. The memories are often very limited, which means that data often has to be stored using a slow sampling rate.

3.5 *Conclusion*

Despite the drawbacks with the programming environment and computational power in DCS systems, the disadvantages with the external computer systems are so serious that one can draw the conclusion that the monitoring tools should be implemented in the DCS systems.

4. IMPLEMENTATIONS

The oscillation detection procedure was first implemented in the single-station controllers ECA400 and ECA600 from ABB. The method is fully automatic in the sense that all parameters are fixed to the values suggested in Section 2. When an oscillation is detected, the front starts to flash and continuous to flash until the alarm is acknowledged. The detection procedure has also an additional function. If the ECA controller is running in adaptive mode, the adaptation is switched off as soon as an oscillation is detected. This is to avoid detuning the controller in case of stick-slip motion caused by friction in the valve. An application of the use of the monitoring procedure in the ECA600 controller is described in the next section.

Both the oscillation detection procedure and the Idle index calculation are implemented in the ABB Industrial^{IT} system, but this system is just released and the experience obtained from this implementation is limited.

The detection procedures have also been implemented in various DCC systems, e.g., from Hartman & Braun, Siemens, and Honeywell, especially in the Pulp and Paper industry. These systems are more or less suitable for this kind of implementation. Some have free-programmable blocks, but in most of the applications the programming has been performed using the standard blocks already available.

One example of such an implementation is made in the paper mill AssiDomän Frövi in Frövi, Sweden, see (Ericsson *et al.* (2002)). The oscillation detection procedure is implemented in a High-Performance Process Manager (HPM) in the Honeywell TDC3000 system. The detection procedure is currently running on-line and supervise over 91% of the control loops in the carton board mill.

Each loop is characterized by its oscillation index, which is increased every time an oscillation is detected. The oscillation index is reset to zero when the controller is tuned or when a maintenance is performed. In this way, it is easy to get a quick historical

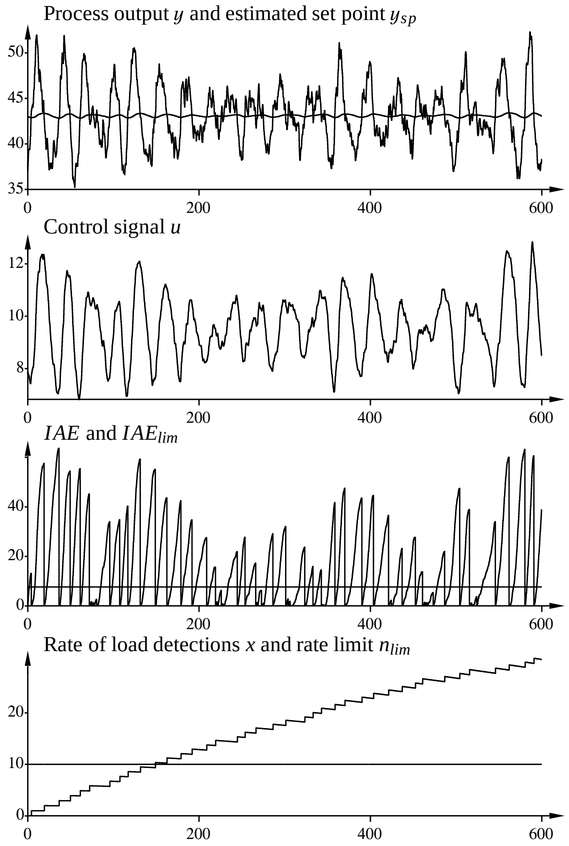

Fig. 2 The oscillation detection procedure applied on a pulp concentration control loop.

overview of the different loops. The most oscillatory loops are presented on a “top-ten list” in the mill-wide information system for proper action by the instrument department. Two examples from the implementation are given below.

5. EXAMPLES

The oscillation detection procedure, implemented in the ECA-600 controller has been applied on various industrial plants with good results. The following example is taken from a pulp concentration control section in a paper mill, where pulp is diluted with water to a desired concentration. The concentration controller was a PI controller with gain 0.33 and integral time 24 s.

Figure 2 shows 10 minutes of data from the loop. The first graph shows the process output, i.e., the pulp concentration, in %. Because of high friction in the water valve, the process is oscillating with an amplitude of a few percent. The first graph also shows an estimate of the set point, since this variable was not recorded. The estimate is simply obtained by a low-pass filtering of the process output.

The second graph shows the control signal in %. The third graph shows the IAE calculated between successive zero crossings of the control error, as well as IAE_{lim}. Since the ultimate period was not available, IAE_{lim} was calculated from the integral time T_i as $IAE_{lim} = 2/\omega_i = T_i/\pi \approx 7.6$. The IAE-values are significantly larger than IAE_{lim}, as can be expected because of the high oscillation amplitude.

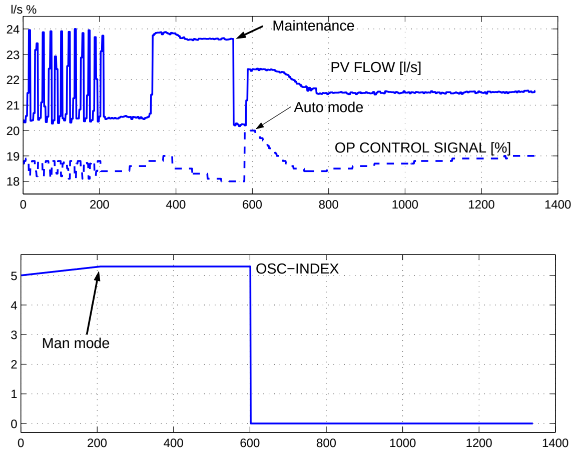

Fig. 3 Stick-slip motion in a flow control loop. The upper diagram shows the process output (solid) and the control signal (dashed). The lower diagram shows the oscillation index.

The fourth graph finally shows the rate of load detections x and the rate limit n_{lim}, both calculated according to the program in Section 2. The rate x exceeds the rate limit n_{lim} after about 3 minutes, and the detection procedure gives an alarm. The rate x converges to about 80, eight times larger than the rate limit. However, in the implemented version x is reinitialized to zero every time x exceeds n_{lim}.

The oscillations are easily noticed in Figure 2. However, process operators seldom have access to these kind of graphs, but are often left with a bar graph with a low resolution. The present oscillation had been present for a long time without being discovered by the process operators.

The last two examples are taken from the implementation in Frövi, see (Ericsson *et al.* (2002)). The first is a flow control loop, where the flow of retention chemicals added directly to the short circulation of the top layer of the board machine is controlled. The chemicals control the retention, which in turn affects e.g. the basis weight. It is, of course, important to keep the flow at a desired level.

Data from the flow control loop are presented in Figure 3. The loop was oscillating, and in this case the oscillations were detected almost immediately, and the control loop was switched into manual mode. The maintenance staff investigated the oscillating loop and found, by performing repeated small step changes in the control signal, that the pilot valve in the actuator suffered from stick slip motion. The action taken was to clean the actuator and switch the mode to auto again.

As shown in Figure 3 the oscillation index was increasing fast and stopped when the mode was switched into

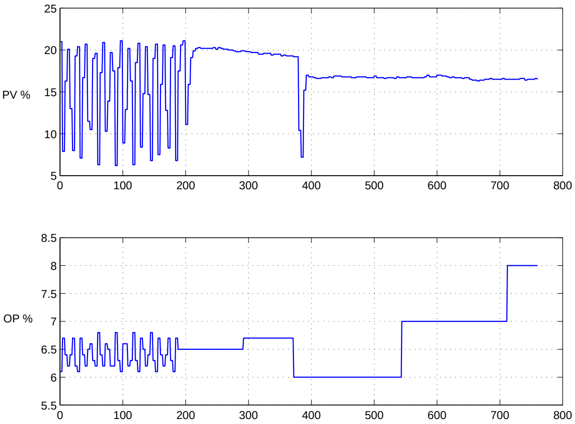

Fig. 4 Stick-slip motion in a differential pressure loop. The upper diagram shows the measurement signal and the lower diagram shows the control signal.

manual. After the maintenance was undertaken the index was reset to zero. The oscillations and the index increase stopped after this maintenance.

The second example shows control of a differential pressure of a steam cylinder in the drying section of the board machine. Disturbances in the differential pressure affect both the steam pressure and the flow of condensed water in the entire steam group.

Data from the loop are presented in Figure 4. This control loop was oscillating, which was discovered from inspection of the “top-ten list”. The loop was investigated, and also in this case the actuator was suffering from stick-slip motion. Figure 4 shows repeated manual step changes of the control signal without any response in the process value. In this case no maintenance could be made without stopping the entire board machine and the controller was left in manual mode until the next stop of production.

6. CONCLUSIONS

Several procedures for automatic performance monitoring have been developed in the last decade. These procedures are now implemented and applied in industry. This paper has focused on various aspects of these implementations.

The monitoring tools should be implemented directly in the DCS systems, and not in external computers. In summary, the reason is that there is so much information needed about the control loops except the values of the signals that are monitored. The operating condition, controller parameters, and values of additional signals are examples of such information. Today, this information is normally not transferred to the external computer systems, but only available inside the DCS system.

Since the implementation often has to be performed using the standard blocks available in the DCS system, it is a prerequisite that the monitoring procedures are simple. Two such simple procedures, for detecting oscillating loops and sluggish loops, respectively, have been presented in the paper.

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