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Managing the Performance of Control Loops with Valve Stiction: An Industrial Perspective

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***Abstract*— Valve stiction is a commonly encountered problem in processing plants. In this manuscript we present an industrial perspective on the problem of detecting and compensating for valve stiction. Some innovative approaches are proposed for detecting valve stiction and determining the tuning parameters that can mitigate the impact of the valve issues.**

I. Introduction

Process control is integral to the safety, operability and profitability of any processing facility. The term process control has come to encompass a wide array of basic and advanced control techniques ranging from proportional-integral-derivative (PID) control to multivariable model predictive control (MPC). Since the 1990's there has been a surge in online control performance monitoring (CPM) & diagnostics technology for both PID and MPC layers ([1][2][3]) More recently the availability of closed loop identification technology ([4]) has opened up the prospect of adaptive control for industrial practitioners.

In many of today's plants, the performance of the process control assets is monitored on a daily basis and compared with industry benchmarks. The monitoring system also provides diagnostic guidance for poorly performing control assets. Many industrial sites have established reporting and remediation workflows to ensure that improvement activities are carried out in an expedient manner. Plant-wide performance metrics can provide insight into company-wide process control performance. Closed loop tuning and modeling tools can also be deployed to aid with the improvement activities.

As part of its process control improvement initiative, Saudi Aramco has deployed CPM technology on approximately 15,000 PID loops, 50 MPC applications and 500 smart positioners across multiple operating facilities. The results from the monitoring tools are incorporated in the continuous improvement process at Saudi Aramco where majority of the loops are monitored in near real-time and a holistic performance picture is obtained for the entire plant.

One of the common reasons for poorly performing control loops is issues with the control valve such as valve stiction, hysteresis and backlash amongst others. Valve stiction is often the culprit of cycling in control loops. A number of online stiction detection algorithms are now available through commercial monitoring technologies. While these techniques are reasonably accurate in estimating stiction in control valves, identifying appropriate tuning parameters for controllers with sticky valves is also a challenging problem. Even though valves with stiction and other issues may be known in an operating facility, carrying out the necessary maintenance activities may take time due to the need to minimize impact on production and quality.

This paper explores through some industrial cases studies the topics of valve stiction detection and compensation of stiction through tuning of PID parameters available to industrial practitioners. Section II focuses on practical approaches to valve stiction detection. A simple sticiton estimation method is proposed using the one parameter model. Section III discusses methods for mitigating the impact of valve stiction on controller performance through appropriate choice of controller tuning parameters. The emphasis is on techniques that can be applied easily in industry and can help address real issues. Section IV presents some concluding remarks and highlights potential areas for research in the area of control performance monitoring.

II. Detecting Valve Stiction

A. Motivating Example

At the Ras Tanura refinery of Saudi Aramco the performance of approximately 2000 PID loops and 26 MPC applications is monitored on daily basis. Controller key performance indicator (KPI) reports are generated on a weekly basis for all the key process areas. These reports in turn trigger established workflows at the site for prioritizing and addressing the underperforming controllers. The continuous monitoring and remediation activities have led to significant improvement in performance of the regulatory and advanced control layers.

Table I lists 20 control loops that were found to be cycling at different frequencies ranging from 2-20 minutes in a particular process area. The oscillation index is a parameter which indicates the strength of oscillation in a loop with 1 representing a perfect sinusoid and 0 being a random signal. As can be seen from the table, a majority of the loops were diagnosed by the monitoring software as having valve stiction to varying degrees (0.3-8.8%). In older facilities the valve packing is often tightened to prevent leaks, especially

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in high pressure systems, and this can often lead to manifestation of stiction.

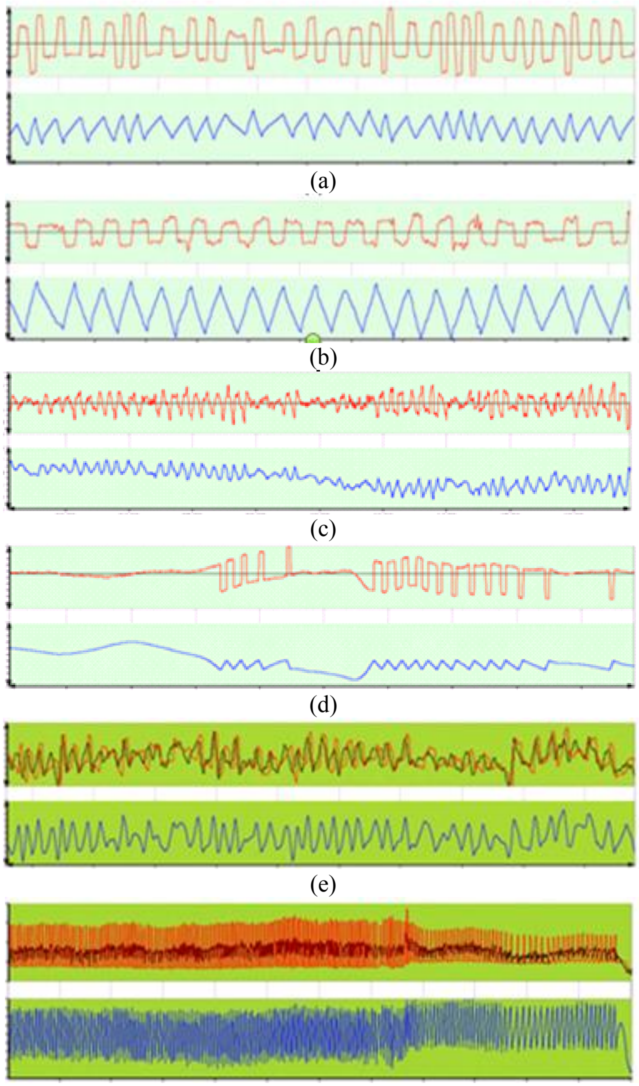
In an operational facility it is not always possible to address the valve issues and carry out the necessary maintenance right away. Absence of bypass lines/valves would mean that one has to wait until the next plant shutdown to fix the mechanical issues with the valve. This means that the plant has to run with the malfunctioning valves for potentially a few years.

TABLE I. LIST OF CYCLING LOOPS

Controller No.	Oscillation Index	Oscillation Period (min)	Stiction
1	0.63	2	-
2	0.63	2	1.8
3	0.71	2.5	-
4	0.7	2.5	-
5	0.72	4	0.91
6	0.8	4.5	0.15
7	0.64	5	2.51
8	0.98	6	8.82
9	0.86	6	-
10	0.49	8	-
11	0.54	8	-
12	0.45	8.5	-
13	0.69	10	0.32
14	0.43	10	3.16
15	0.62	10.5	0.77
16	0.59	10.5	-
17	0.46	12.5	1.06
18	0.94	14	-
19	0.79	17	0.49
20	0.74	17.5	1.72

All valve stiction detection methods can suffer from false positives and false negatives. Hence it is important to validate the reported valves stiction through established procedures. The CPM technology being used at this facility uses the bicoherence based stiction estimation approach first developed by [6]. Studies have been carried out comparing the performance of different stiction detection methods ([9]).

Fig. 1 shows the process variable (PV), setpoint (SP) and controller output (OP) trends for some of the control loops in Table 1 over a 24 hour period. Some of the loops exhibit the classic sawtooth pattern of the stick-slip cycle caused by valve stiction. Others do not show the stiction signature as clearly but the stiction is present to varying degrees. All of the loops shown in fig. 1 are flow loops. Figs. 1(e)-(f) show valve stiction in loops which are secondary flow loops. One can see the effects of the primary-secondary interaction in fig. 1(e) and 1(f) where the setpoint of secondary is also cycling at the same frequency as the process variable.



(a)
(b)
(c)
(d)
(e)
(f)

Figure 1. PV(red), SP (black) and OP (blue) trends of loops with valve stiction. Light green background indicates that the loop is automatic while the dark green backgroufand indicates that the loops is in cascade mode.

Fig. 2 shows data from a smart positioner for a flow loop which was found to show valve stiction. Smart positioners are common in newer plants and make accurate detection of valve related problems easier due to the availability of the actual valve stem position from the field.

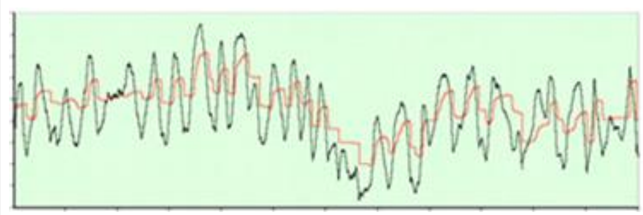


Figure 2. Controller output (black) and valve position (red) data from a smart position showing valve stiction.

B. Review of current methods

Detection of valve stiction has been a topic of intense activity in the recent past. The modeling approaches for stiction range from mechanistic to data-based ([5][6][7][8]). [9] present a detailed comparative analysis of a number of stiction detection algorithms. Most of the sticiton models use a two parameter approach based on the static (f_s) and dynamic friction (f_d) experienced by the control valve. The relative amount of these two types of friction characterizes the valve motion starting of a state of rest. These aspects are very well illustrated in [5].

C. Proposed Technique

Here we propose a simple two-step approach to estimating valve stiction. To start with a stiction model is adopted to describe the valve stiction. For the sake of simplicity Stenman's one parameter model ([7]) was evaluated in this study. The parameters in the stiction model and the dynamic model parameters – time delay (τ_d), time constant (τ) and gain (K) – form the unknown parameters that are to be estimated. Akaike's information criterion (AIC) was selected as the fit criterion:

$$AIC = NlogV_N + 2p,\ V_N = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \quad (1)$$

p is the number of parameters, N is the number of data points, y_i are the PV measurements and $\hat{y}_i$ are the predictions of the combined, stiction and dynamic, model. An initial estimate is provided for the amount of stiction and the following algorithm is used to minimize the fit criterion until convergence is achieved:

1. Assume stiction $\hat{S} = \hat{S}_0$
2. Estimate the dynamic model parameters($\hat{K}$,$\hat{\tau}$,$\hat{\tau}_d$) for the current value of stiction. A first order ARX model structure was used and the parameters estimated using the least squares solution.
3. Calculate a new value for $\hat{S}$ that minimizes AIC using a numerical optimization solver
4. Iterate 2-3 until convergence is achieved

The advantage of the proposed technique is that it does not approximate the stiction model using any other model structure. In future more sophisticated stiction models will be incorporated into the proposed algorithm. Note that the proposed technique can work with closed loop data. On the other hand the convergence properties of the proposed algorithm would have to be studied further and convergence to a local minimum is a possibility.

It is important to have the stiction model and dynamic model estimated separately as this facilitates better design and compensation for the stiction. Moreover it allows the control engineer to estimate the valve stem position based on the stiction model. The dynamics for most simple loops are fairly well known. For example a liquid flow loop will typically have $\tau<=5s$, $\tau_d<=1s$.

D. Simulation Example

A set of benchmark problems were created based on the one parameter stiction model to test the proposed algorithm. Fig. 3 shows the effects of ignoring stiction during the model identification step on one of the test problems where $K=2$, $\tau=5s$, $\tau_d=1s$ and $S=2\%$. If the stiction is not considered carefully during the identification step and a linear dynamic model is identified it often results in large estimated delays and time constants compared to the true values. In this case the model parameters were estimated as $\hat{K}=1.25$, $\hat{\tau}_d=50s$ and $\hat{\tau}$ = $63s$. The resulting model fits the data quite poorly as can be seen from the top graph in figure 3. The gain estimate is also biased as a result of incorrect model structure.

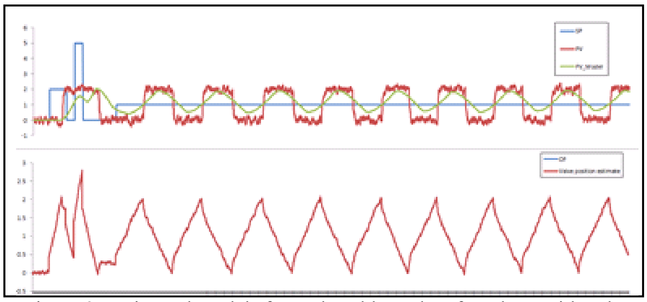


Figure 3. Estimated models from closed loop data for a loop with valve stiction (green line – model prediction, red – process output, PV). Bottom graph shows the controller output.

Fig. 4 shows the results when stiction is estimated using the proposed algorithm. In this case the stiction was estimated to be $\hat{S}=1.99\%$ and the dynamic model parameters were estimated as $\hat{K}=1.99$, $\hat{\tau}_d=1s$ and $\hat{\tau}$ = $5s$. The model fit was excellent. There was no external excitation added to the loop during this time period.

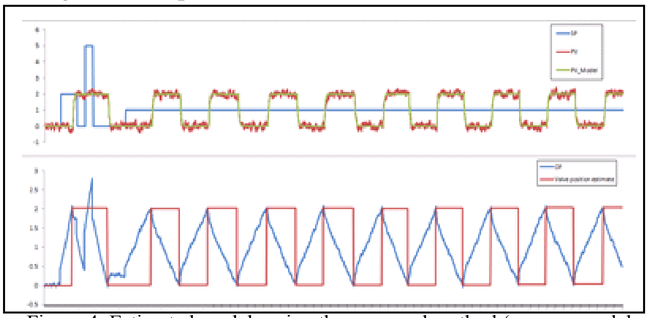


Figure 4. Estimated models using the proposed method (green – model prediction, bottom graph shows the controller output in red and estimated valve position in blue)

E. Industrial Case Study

Next the proposed algorithm was tested on one of the loops identified with valve stiction in Figure 1. The loop showed clear evidence of valve stiction in the form of a stick slip cycle. A smaller section of the 24 hour time period was selected for carrying out identification. The estimated model parameters were: $\hat{S}$= 0.63, $\hat{K}$= 0.56, $\hat{\tau}=21s$, $\hat{\tau}_d$ =$5s$.

The estimated valve stiction is in agreement with the stiction amount reported by the bicoherence based technique. The model prediction shows good agreement with the measurement. The results in fig.5 also highlight another fact – real valves do not always display a fixed amount of stiction. The amount of stiction exhibited can be a function of the direction of the valve movement, the valve position itself and a number of other factors which cannot be measured directly.

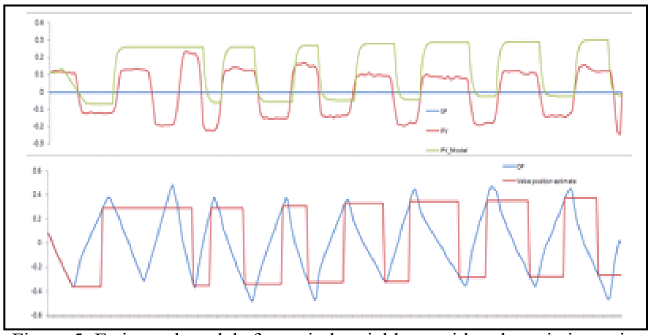


Figure 5. Estimated models for an industrial loop with valve stiction using the proposed technique

III. COMPENSATING FOR STICITON

A. *Review of existing techniques*

In an industrial context a limited number of tuning parameters are available to minimize the impact of valve stiction. [11], [12] suggest detuning the integral action to avoid the stick-slip cycling due to stiction. [10] suggests using deadband reset scheduling which involves detuning the integral action when operating within the stiction band. This is a practical approach as one cannot hope to control the process variable to a resolution finer than the one presented by the amount of stiction times the process gain. However not all industrial control systems may have the deadband reset scheduling algorithm available as a standard option.

From a research perspective a number of options have been explored ranging from nonlinear control techniques ([13]) to addition of dither or a knocker signal ([14][15]). The design of this knocker or dither signal in itself is a complex task. A two-step compensation signal is shown to have significant improvement in [16]. In [17] a frequency response based technique is proposed for analyzing the closed loop behavior of a sticky valve for a given set of tuning parameters. Some rules are proposed to determine a stable set of proportional and integral tuning parameters for self-regulating and integrating processes.

B. *Proposed techniques*

In this section we explore (a) the frequency response analysis techniques described in [17], (b) the impact of adding derivative action on sticky valves and (c) a numerical optimization approach to determining the PID tuning parameters for a sticky valve.

The frequency response techniques work by formulating a describing function for the valve stiction model. The open loop transfer function and the describing function are plotted as function of frequency (see Fig. 8 as an example). If these two intersect then loop will oscillate due to the valve stiction. If the tuning parameters (proportional and integral) are chosen such that the two curves do not intersect then the loop is not expected to cycle. This approach presents an elegant and easy to understand method for analyzing the impact of tuning parameters on a loop with valve stiction.

As an extension to the frequency approach, the derivative term was included in the loop tuning parameters. While derivative action is typically used only for loops with relatively large time delays, the presence of valve stiction is in some ways akin to adding time delay. This can be seen from the results in fig. 3 where the time delay is estimated to be a large value when stiction is not considered explicitly. Moreover the presence of derivative action leads to constant movement of the controller output which in some ways is similar to adding dither.

However one needs to be very careful in selecting the right amount of derivative action as excessive derivative can lead to inordinate valve movement and potentially cause instability in the loop. The frequency response techniques give a systematic way of choosing the derivative term as well.

The last approach considered was a purely numerical optimization approach. With the presence of stiction, the closed loop becomes a nonlinear system and hence the control objectives such as control error and input variance become nonlinear functions of the controller tuning parameters. A constrained optimization problem was formulated over a finite horizon to minimize a weighted sum on input and output variances (similar to LQG) with the degrees of freedom being the controller tuning parameters, within reasonable constraints based on industry experience. The derivative term was included as an optimization variable as well:

$$\min_{K_c,T_i,T_d} \sum_{i=1}^{N}[w_1(r_i - y_i)^2 + w_2 u_i^2] + w_3(r_N - y_N)^2 \quad (2)$$

$$s.to. K_c \in \{0,10\}, T_i \in \{5,600\}, T_d \in \{0,60\}$$

where w_1, w_2, w_3 are the relative weighting terms.

C. *Simulation Example*

A first order plus dead time process is considered with the following parameters: $K=1$, $\tau=5s$, $\tau_d=1s$ and $S=2\%$. Using a controller with $K_c=0.5$ and $T_i=20s$ leads to the stick-slip cycle in fig. 6, following a step change of 4 units in the setpoint.

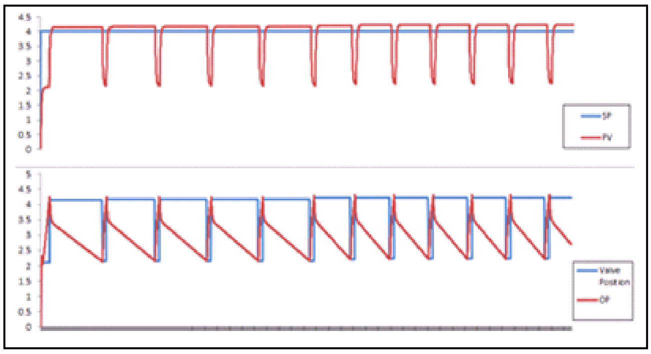


Figure 6. Closed loop simulation of a sticky valve with a stick-slip cycle.

Using guidelines discussed in [11],[12] and the frequency response analysis in [17], the integral action was detuned and the integral time T_i was increased to 200s. The resulting behavior is shown in fig. 7 and the frequency response analysis in fig. 8. The loop now exhibits stable behavior but somewhat slow response. Next the effect of derivative action was evaluated by introducing a non-zero derivative term.

The base case tuning was the one shown in fig. 6 where $T_i=20s$ and $K_c=0.5$.

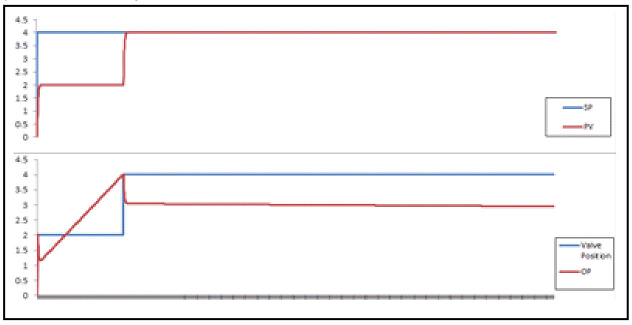


Figure 7. Detuned integral action – resulting in stable behavior.

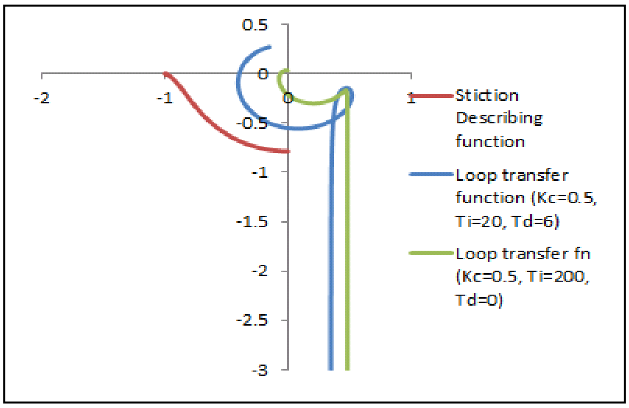


Figure 8. Frequency domain analysis of the tuning parameters.

A derivative time constant of $T_d=6s$ was chosen based on the frequency domain analysis. The effect of adding the derivative term is illustrated in fig. 8, it can be seen the loop transfer function is now closer to the describing function curve. This results in more aggressive control action and keeps the valve moving as can be seen in fig. 9. While the frequency analysis techniques were found to provide sound directional guidance, they do not provide precise values. For example for the first case where $K_c=0.5$, $T_i=20$ the frequency analysis suggests that there should not be any oscillation however the stick-slip cycle is observed. This may be due to the approximate nature of the describing function analysis.

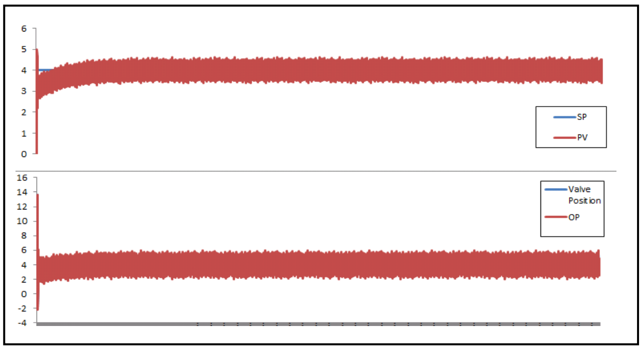


Figure 9. Effect of including derivative action on a sticky valve

The control loop performance for the 3 cases is compared in Table II. It can be seen while case 3 ($T_d=6s$) gives the best performance in terms of control error variation, it comes at a price. The valve movement is orders of magnitude higher compared to the other cases. Part of this could be attributed to the derivative kick on the setpoint change which can be disabled in practice.

The numerical optimization technique was initialized with Case 1 tuning values and the objective function was exclusively focused on minimizing error variance and offset ($w_2=0$, $w_1=w_3=0.5$). The tuning parameters obtained thus are shown in cases 4 ($T_d=0$) and 5 in Table II. Notice that in the case 4 the procedure chose K_c value that is just above the stiction value. This helps in ensuring that the valve is kept moving and can respond to dynamic changes quickly. In general the new tuning parameters asked for higher gain and reduced integral action which is consistent with industrial experience.

TABLE II. COMPARISON OF LOOP PERFORMANCE

Loop KPIs	**Case 1 (K_c=0.5 T_i=20 T_d=0)**	**Case 2 (K_c=0.5 T_i=200 T_d=0)**	**Case 3 (K_c=0.5 T_i=20 T_d=6)**	**Case 4 (K_c=2.01 T_i=301 T_d=0)**	**Case 5 (K_c=1.32 T_i=196 T_d=1)**
Error Variance	0.69	1.00	0.43	0.49	0.26
Valve travel[a]	12.18	4.01	449.29	108.45	55.84
OP Variance	0.69	0.99	1.22	0.8	0.54

a: Valve travel is the sum of absolute moves made by the controller. This is a practical performance measure for a control loop.

D. Industrial Case Study

In this section we show the impact of tuning on two loops with valve stiction. Both are flow loops and here on referred to as Loop 1 and Loop 2. Loop1 was a feed flow loop to a distillation column and Loop 2 is a reflux loop on another distillation column. Both are important loops and can have impact on the throughput as well as quality. Both these loops were diagnosed as having valve stiction by the monitoring software. After validating the siciton, it was determined that the valve maintenance activities could not be carried out in the short term. Hence it was decided to retune these loops to minimize the impact of stiction.

The goal was to retune the proportional and integral tuning parameters to improve loop performance. It was determined that the integral action was too aggressive in both cases. Subsequently through closed loop modeling and a series of trial and error steps, the integral action was detuned on both loops. The proportional action in the case of Loop 2 was increased to ensure that the speed of response was not compromised.

Fig. 10 and fig. 11 show the *before* and *after* trends of the two control loops over a 24 hour period. Tables III and IV compare the control loop KPIs, before and after the tuning was carried out. As can be seen from the trends and tables significant improvements were achieved in terms of (a) loop stability (b) valve travel (c) variability and (d) settling times. The disadvantage of detuning the integral terms without increasing the proportional term is that the rise time or the speed of recovery from a disturbance tends to be slower. The improvements were achieved with a relatively small amount of effort and leveraged the existing historical data. No intrusive testing was necessary and the loops did not have to be put in manual.

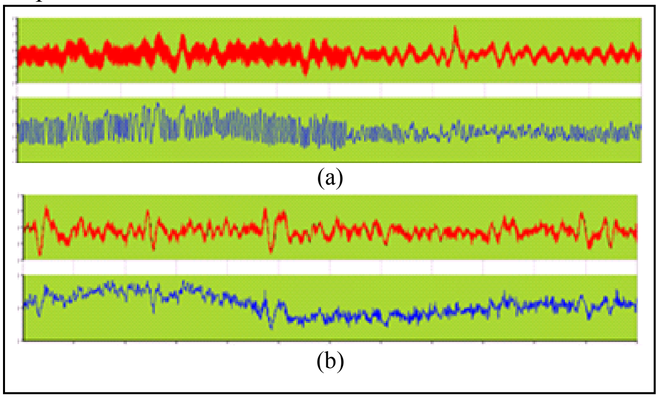


Figure 10. Control loop performance of Loop 1 before (a) and after (b) tuning to compensate for a sticky valve (PV-red, SP-black, OP-blue)

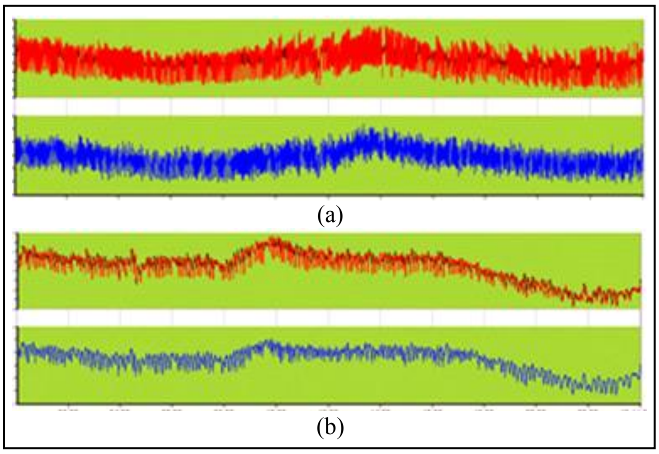


Figure 11. Control loop performance of Loop 2 before (a) and after (b) tuning to compensate for a sticky valve (PV-red, SP-black, OP-blue)

TABLE III. LOOP 1 BEFORE AND AFTER COMPARISON

KPI	Before	After	Change
Standard Deviation	336	90	-73%
Valve travel	250	86	-67%
Settling time (min)	240	2.25	--99%
Oscillation Index	0.84	0.4	-52%

TABLE IV. LOOP 2 BEFORE AND AFTER COMPARISON

KPI	Before	After	Change
Standard Deviation	1.1	0.45	-59%
Valve travel	1706	404	-76%
Settling time (min)	39.25	3.5	-91%
Oscillation Index	0.6	0.39	-35%

It may not be always possible to completely eliminate the sticiton related cycling through retuning. However as the above examples demonstrate there is potential to better *manage* the valve sticiton through smarter choice of tuning values. The improvements were achieved with reduced control effort as well.

IV. CONCLUSIONS & FUTURE DIRECTIONS

In this work we have described some practical closed loop approaches to stiction estimation and compensation using existing controller tuning parameters. Simulation and industrial examples were used to demonstrate the applicability of the proposed techniques. The impact of adding derivative action was assessed and an optimization based technique evaluated on simulation examples. A single environment to estimate, simulate, analyze and tune for stiction in the closed loop is important for control engineers to make the right choice of tuning parameters. Tuning sticky valves appropriately can have a big impact on process stability and the advanced control layer as well. Estimation of optimal tuning parameters for loops with valve stiction can be an area of future research. The ability to add external signals to compensate for sticiton is still not commonly available in industrial control systems. The area of control performance monitoring has made good strides in the past decade in terms of the ability to assess and diagnose individual control loops. However more work is needed to increase *awareness* of process operation and control strategies which go beyond the single loop control in CPM.

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