Proceedings of the 9th International Symposium on
Dynamics and Control of Process Systems (DYCOPS 2010),
Leuven, Belgium, July 5-7, 2010
Mayuresh Kothare, Moses Tade, Alain Vande Wouwer, Ilse Smets (Eds.)

Modified PI Controller for Stiction Compensation

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Abstract: Stiction is a well known problem of the process performance. Compensate its effect is essential, because most of sticky valves cannot be replaced and they remain working for months or years. The scope of this work is to propose a novel methodology to compensate stiction effects, through the modification of the controller (PI) block in the control loop. The proposed approach is based on the two moves method, however it allows to specify closed loop performances faster than open loop and reject load disturbances efficiently. We assume here that a small offset between process variable and setpoint is accepted, what decreases significantly the valve traveling, comparing with available approaches. The method is described for both setpoint tracking and disturbance rejection. The efficacy is corroborated by a case study, considering setpoint changes and disturbance rejection.

Keywords: Performance Monitoring, Valve, Static Friction, Hysteresis, Stiction Compensation.

1 INTRODUCTION

Control loop performance has been a productive field for academy and a profitability issue for industry in the last two decades. Since the first work of Harris (1989), automatic methodologies provide on-line measurements to evaluate loop performance. Inside this scope, one well known villain is valve stiction. Many surveys corroborate this “valve illness”, showing that around 30% of all valves have a degree of stiction that can affect loop performance (Bialkowski, 1993; R. Srinivasan & Rengaswamy, 2005).

Oscillation is the first sign that the loop can have high static friction. Once the oscillation is detected (Hagglund, 2005; Thornhill & Hägglund, 1997), then the stiction can be diagnosed. Several methodologies are available in the literature to fulfill this job (He, Wang, Pottmann, & Qin, 2007; Horch, 1999; Jelali & Huang; Rossi & Scali, 2005; Ruel, 2000; Scali & Ghelardoni, 2008; Singhal & Salsbury, 2005; Stenman, Gustafsson, & Forsman, 2003; Yamashita, 2006). Besides, some works have proposed specific stiction models for diaphragm type valves (Chen, Tan, & Huang, 2008; Choudhury, Thornhill, & Shah, 2005). A good survey about stiction models was recently written by Garcia (2008).

Furthermore, some methodologies to compute stiction parameters in real time have been proposed. Choudhury et al. (2006) proposed two methods to quantify stiction parameters, based on ellipse fitting and *c-clustering*. Subsequently, some authors have proposed to quantify stiction parameters using a more reliable model, with two parameters (Choudhury, Jain, & Shah, 2008; Jelali, 2008).

Despite the economical impact of stiction in the process, fix this problem for all valves is economically unviable. Thus, not only diagnose and quantify stiction is important, but also compensate or decrease its impact is essential. In the literature, several methodologies are available to compensate the stiction (Hagglund, 2002; R. Srinivasan & Rengaswamy, 2005; Ranganathan Srinivasan & Rengaswamy, 2008). In section 2, some of them will be depicted and the main limitations highlighted.

In section 3, an adapted PI algorithm for sticky valves is proposed. The method is based on two moves algorithm (Ranganathan Srinivasan & Rengaswamy, 2008) and allows closed loop performance faster than open loop as well good disturbance rejection. Moreover, the proposed controller has small output variability, what can increase the life of a valve.

In section 4, the validity of the proposed method is corroborated through case studies. The paper ends with the concluding remarks.

2 BACKGROUND

Stiction, or high static friction, can be defined as the valve damage that keeps the stem from moving, because the static friction exceeds the dynamic. As a consequence, the force to move the steam is generally larger than the desired new stem value, and the movement is jumpy (Ruel, 2000).

2.1 Stiction: model

A sticky valve has in the phase plot (valve output (MV) versus controller output (OP)), shown in Fig. 1, four stages: deadband (*DB*), stickband (*SB*), slip jump (*J*), and moving phase (*MP*). We assume that the process and controller have linear behavior, while the sticky valve is the source of loop nonlinear behavior (Choudhury, et al., 2005).
When the valve changes the direction (A), the valve becomes sticky. The controller should overcome the deadband (AB) plus stickband (BC), and then the valve jumps to a new

position (D). Next, the valve starts moving, until its direction changes again or the valve comes to rest, between D and E.

The stiction model consists of these two parameters: S, called staticband, (deadband+stickband) and J (slipJump). The deadband and stickband represent the behavior of the valve when it is not moving, although the input of the valve keeps changing. The magnitude of staticband and slipjump is essential to determine the limit cycle amplitude and frequency.

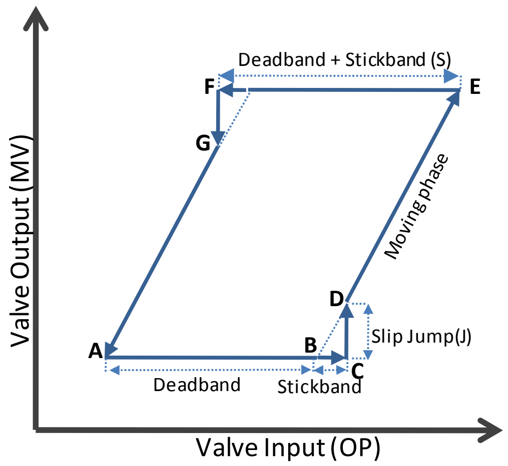

Fig. 1. Relation between controller output (OP) and valve position (MV) for a sticky valve.

A simple model will be used in this work. It assumes that S and J are equal and there is no moving phase. This model is called Stenman model (Garcia, 2008) and is described by:

$$x(t) = \begin{cases} x(t-1) & if|u(t) - x(t-1)| \le d \\ u(t) & otherwise \end{cases} \qquad (1)$$

where $x(t\text{-}1)$ and $x(t)$ represent respectively past and present stem positions, $u(t)$ is the actual controller output and d is the valve stiction band.

2.2 Stiction: compensation

This section describes some methods suitable to compensate valve stiction for pneumatic valves. The approach of Kayihan and Doyle III (2000) is the first algorithm to compensate valve stiction. It requires a valve model with the valve parameters, as well as the plant model. Thus, its industrial application is restricted.

The second work, proposed by Hagglund (2002), suggest to add short pulses, known as "knockers", to the control signal changes. These pulses have equal duration and amplitude in the direction of the rate of chance of the control signal.

The block diagram of the new procedure is illustrated in Fig. 2.

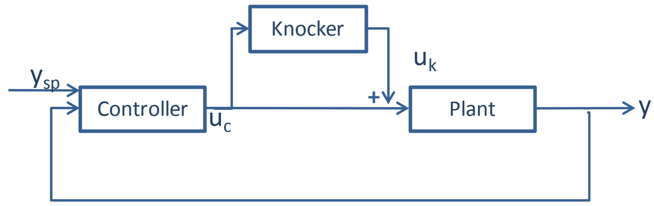

Fig. 2. Block diagram showing the knocker block in the feedback loop.

Control signal $u(t)$ is given by:

$$u(t) = u_k(t) + u_c(t) \qquad (2)$$

Where $u_k(t)$ is the knocker output and $u_c(t)$ is the controller output. The knocker pulse is characterized by three parameters: h_k is time between each pulse, a is the pulse amplitude, and the pulse width τ, as illustrated in Fig. 3.

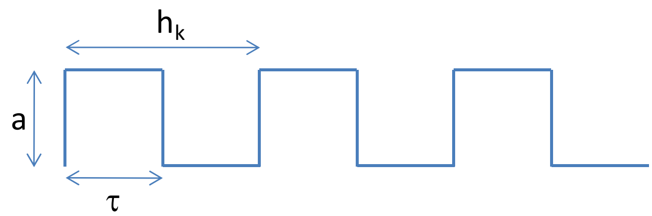

Fig. 3. Knocker pulse representation.

This procedure can be easily applied in industrial valves, because only the stiction parameter (d) should be known. However, tune the knocker parameters is not straightforward. Srinivasan and Rengaswamy (2005) validate the knocker approach and proposed a heuristics to tune the knocker.

Following, the same authors (Ranganathan Srinivasan & Rengaswamy, 2008) have proposed two new approaches to compensate valve stiction. In both, the compensator is inserted between controller and plant, as shown in Fig. 4.

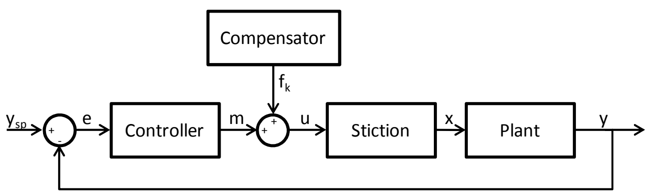

Fig. 4. Control loop with a compensator.

Where: m is the controller output, f_k is the compensator action, y_{sp} is process setpoint, y is process output, e is the error, u is the additive signal ($m + f_k$) that is being fed to the valve and x represents the stem position.

The first approach, called two moves, is based on the idea that the "stiction compensator" should push the valve stem to its steady-state, after a number of moves. After that, the stem remains stick.

The two compensative moves (f_k and f_{k+1}) for stiction compensation are:

$$(f_k)_t = |m_t| + d \qquad (3)$$
$$(f_k)_{t+1} = -m_{t+1}$$

This method requires the exact stiction (d) quantification, the plant should be stable and perfectly known and the process should not be affected by disturbances or white-noise.

Comparing the idea of the two methods (knocker and 2 moves), in the first, the valve is continuously changing, what deteriorates its life-cycle. In the second, the valve will move only when is necessary. On the other hand, if the process is affected by disturbances, the two moves method will constantly move the valve position. If the process is affected by disturbances, the stem behavior will be similar to knocker action.

In the same paper, Srinivasan and Rengaswamy (2008) propose another method for stiction compensation, based on an optimization procedure. The cost function should be minimized, using the compensator moves (f_k) as optimization variables.

$$\min_{f_k} J = \lambda_1 ISE_y + \lambda_2 Var(x) + \lambda_3 \phi(x) \qquad (4)$$

Where ISE_y is the integral square error of PV, $Var(x)$ is the valve stem variability, and ϕ (x) represents the valve aggressiveness. The optimization is performed over defined prediction horizon. λ_1, λ_2 and λ_3 represent either the cost associated for product variability or the penalty for valve variability.

Recently, Ivan and Lakshminarayanan (2009) proposed a new approach for stiction quantification and compensation. In their work, first the stiction is diagnosed using traditional methods. Then the stiction is quantified, using a one-parameter model, using a Hammerstein approach, similar to Srinivasan et al. (2005). The stiction is compensated using the concept of *constant reinforcement* (CR). The idea behind the method is similar to the knocker, however it adds a constant signal ($\alpha(t)$) to the controller output.

$$\alpha(t) = a.sign(\Delta u) \qquad (5)$$

2.3 Limitations of the previous methods

The methods to compensate stiction can be divided in two groups. The first, where knocker and *constant reinforcement* are included, the stem is constantly moving to overcome the stiction. This effect can deteriorate the valve, decreasing its operating time. Thus, to apply the previous methods in industrial valves is difficult, because they usually operate months or even years without maintenance.

Consequently, a more parsimonious stiction compensator should be proposed. The two moves method agrees with this idea: the stem will move only when is necessary. However, it has two main constraints. First, when the setpoint changes, the second movement leads the stem to its final value, what makes the controller performance very poor (approximately equal to the open loop). Besides, if the process is constantly affected by disturbances as well the plant model is not well known, the compensator action is also "angry".

The optimization procedure can lead to better results than the remaining methods, using the valve with parsimony. However, tuning the parameters is a difficult task and this procedure is computationally expensive to be applied in all sticky valves in a DCS.

The contribution of our work is lead by the previous ideas: to propose a novel stiction compensator that allows the controller to achieve a faster performance and use the (sticky) stem only when is necessary to avoid valve maintenance. The method is based on the two movement method, however no block is added – a PI controller is modified to be tailored for sticky valves. The "stiction PI" is suitable for process with constant disturbances and fast responses should be performed when setpoint changes.

3 PROPOSED METHOD

As mentioned above, the proposed method aims to adapt the traditional PI controller for scenarios where stiction is present.

Initially, the policy for setpoint changes will be introduced, and then, for disturbance rejection. As previous discussed the two moves method allows the "smooth stiction compensation", where the valve is not over-demanded. This is the core idea of this work: extend this method for better setpoint tracking and disturbance rejection.

Fig. 5 shows the original two moves method reaction for a setpoint change.

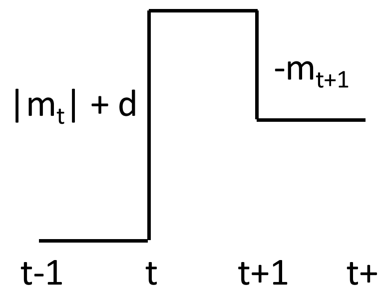

Fig. 5: Wave-shape of the original two moves method.

The proposed method has two differences between the original two moves approach. The first movement can have a larger overshoot than $|m_t| + d$ and the second movement can be applied during more than one sampling interval. These two movements allow not only the controller overcome the stiction, but also to perform faster than open loop. Fig. 6 shows the proposed two moves wave shape.

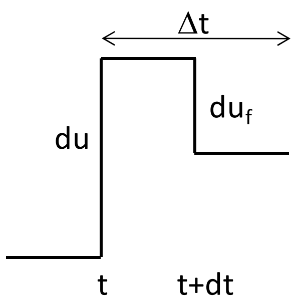

Fig. 6: Wave-shape of the proposed method.

The values for *du* and *dt* can be computed based on the desired closed loop performance (e.g. rise time (*rt*)). Assuming a first order plant, these parameters can be computed using the following relations:

$$du = \frac{0.95dy}{K\left(1 - e^{-\frac{rt}{\tau}}\right)} \qquad (6)$$

$$dt = rt \qquad (7)$$

Where *rt* is the desired closed loop rise-time, *K* and τ the process gain and time constant respectively and *dy* the setpoint change. The user should tune also the window size (*Δt*), which provides the distance between each pair of moves. Based on *Δt*, the user can adjust the valve demand – decreasing values imply in frequent valve actions.

Depending on the stiction magnitude, or the desired closed-loop rise-time, the first movement (*du*) can be smaller than the minimum necessary to overcome the stiction. In this case, the methodology become similar than the two moves.

If there is a model mismatch or the process is constantly affected by disturbances, a modification of the previous relations should be posed. Here, we assume that a small offset between setpoint and process variable (*OFS*) is accepted to avoid constant valve movement. Only if an offset larger than the *OFS* is detected, a corrective action is taken. In this case, the two movements are computed based on the same relations (6 and 7), using the same or a specific closed loop rise-time.

4 CASE STUDIES

In this section, we will show a simulated application of the proposed method. Moreover, a comparison between the proposed approach and knocker will be presented.

The parameters for the plant and the PI with stiction compensator are shown in Table 1.

Tab. 1: Parameters for both plant and PI compensator

Parameter	Value
Plant	$\frac{1}{50s+1}$
Δt	30
OFS	0.001

The Δt parameter has been set based on the desired closed loop rise time, and OFS is set based on the desired offset in the process variable.

In the first analysis, the controller response for a setpoint change using several closed loop rise times is shown (Fig. 7), where both process variable (PV) and controller output (OP) are plotted. Moreover, the original two moves response is also illustrated.

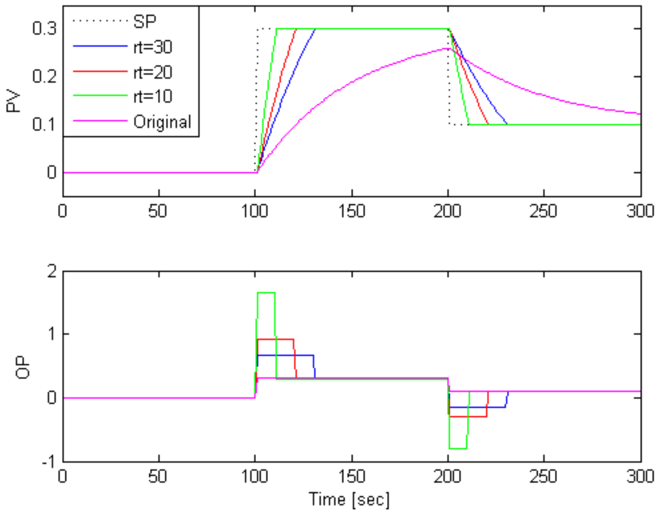

Fig. 7: Closed loop performance for setpoint tracking using the proposed stiction compensator.

Based on Fig. 7, we can affirm that the proposed stiction compensator can lead to faster responses than the original approach.

Fig. 8 shows the regulatory behavior for a load disturbance.

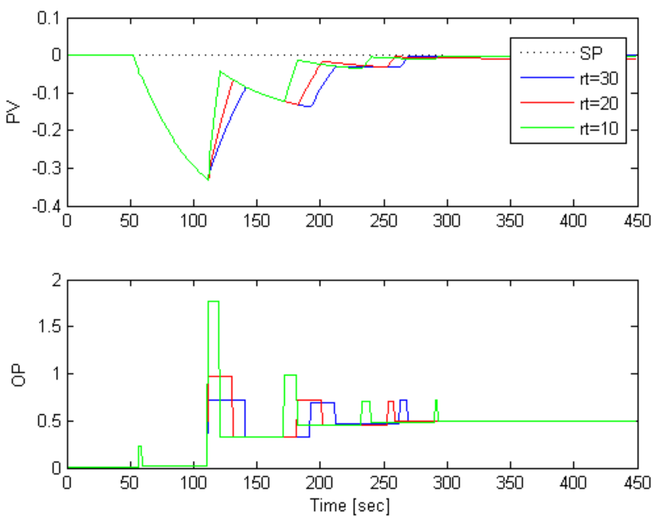

Fig. 8: Closed loop performance for setpoint tracking using the proposed stiction compensator.

Fig. 8 shows the good load disturbance performance for the proposed method. If a narrow performance is required a smaller offset (OFS=0.002) can be used. Fig. 9 shows the controller response for this scenario.

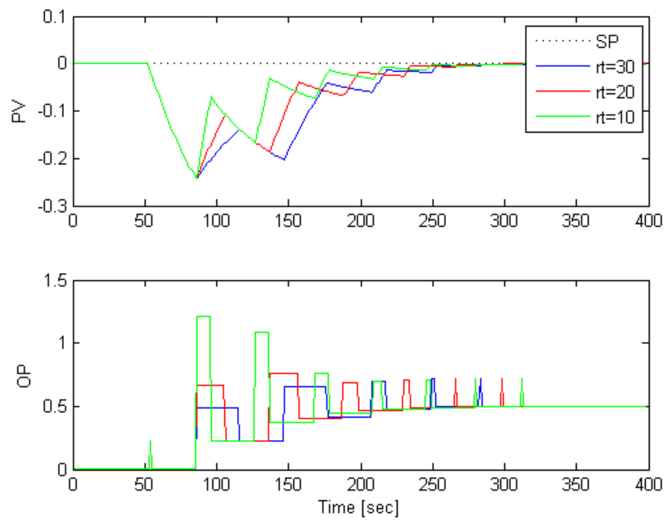

Fig. 9: Closed loop performance for setpoint tracking using the proposed stiction compensator.

Comparing Fig. 8 and Fig. 9, it is clear that decreasing the offset, the response for disturbance rejection becomes faster. However, the valve action becomes more recurrent.

In a more reliable scenario, where a gain mismatch of 20% is inserted, the validity of the proposed approach is corroborated. The response for setpoint change and disturbance rejection is presented in Fig. 10.

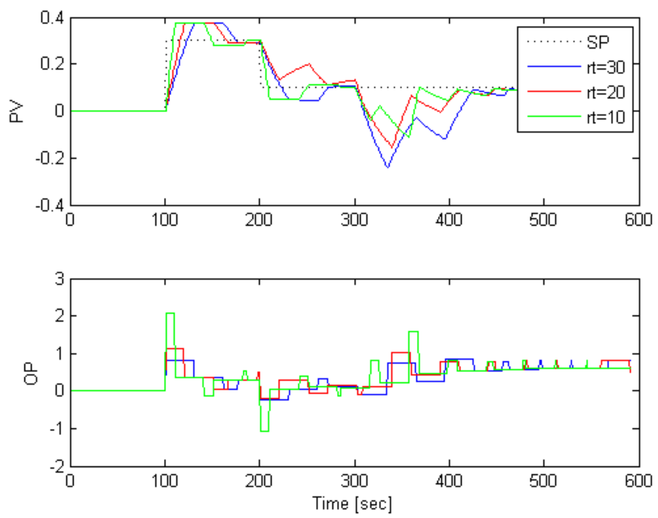

Fig. 10: Closed loop performance for setpoint tracking using the proposed stiction compensator.

Fig. 10 corroborates the validity of the proposed approach, where the setpoint was tracked, with reference changes and load disturbances.

In the last study, the comparison between the proposed method and the knocker, for a system with variable setpoint and load disturbances is illustrated in Fig.11. In this case, the knocker parameters have been tuned using the methodology proposed by Srinivasan and Rengaswamy (2005).

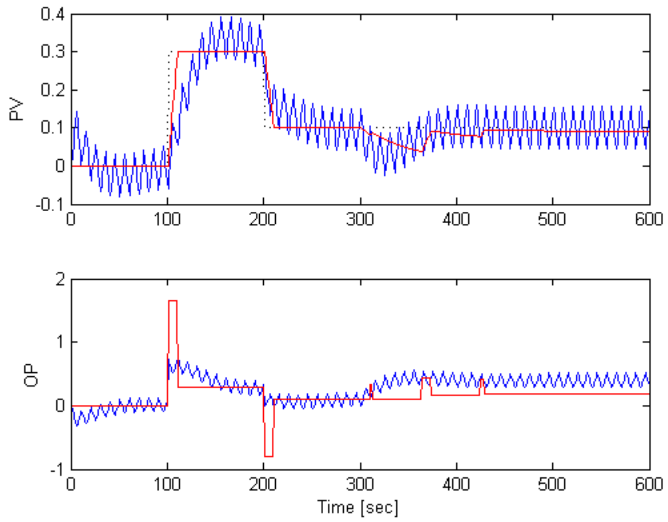

Fig. 11: Comparison between the knocker (blue line) and the proposed stiction compensator (red line).

Fig 11 clearly shows that the proposed approach imposes a smoother valve operation, comparing with the knocker method. In this case, not only the valve deterioration is smaller, but also the performance for both setpoint tracking and disturbance rejection is better.

5 CONCLUSIONS

The main conclusions of the proposed work can be summarized as:

Stiction compensation methodologies are required – despite the fact that a large number of sticky valves is working in industry without maintenance, the number of stiction compensation methods is scarce.

The available methodologies for stiction compensation deteriorate the valve – Moreover, the available methodologies try to overcome the stiction by the insertion of constant valve steps, what decrease the valve life expectancy. On the other hand, the two moves approach can increase the valve life, but it imposes a poor closed loop performance.

New PI algorithm tailored for sticky valves is proposed – in this work a modified PI controller was proposed based on two moves approach, for both setpoint tracking and disturbance rejection. This algorithm allows the process to achieve a faster performance than open loop and reject load disturbances, depending on the tuning parameters.

Successful applications of the proposed algorithm – the proposed algorithm was applied in a set of case studies, where reliable results were provided. Moreover, it was tested against the knocker algorithm and better results were seen.

ACKNOWLEDGMENTS

The authors are very grateful for the grants from PETROBRAS / BRAZIL.

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