AUTOMATIC DETECTION OF STICTION IN ACTUATORS: A TECHNIQUE TO REDUCE THE NUMBER OF UNCERTAIN CASES

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Abstract: The presence of stiction in actuators is responsible for deterioration of performance in control loops: the possibility of automatic detection of this phenomenon from the analysis of recorded data is certainly very important and should be included in a monitoring system. In the paper it is shown that the application on plant data of a largely diffused technique (Horch, 1999), may not be able to detect the presence of stiction in some cases. More in general, application of the technique in simulation on different stiction models, shows that, by varying process parameters, stiction can be hidden and the uncertainty zone (gray zone: where is not possible to take any decision) may become very large. A new technique, based on the shape of loop signals originated by stiction, is then proposed. Even though it is not able to guarantee detection of friction phenomena in all cases, (impossible for every technique, without any further knowledge on the process), the proposed technique allows a significant reduction of the gray zone; this is illustrated by intensive simulation and by application on plant data.

Keywords: Process Monitoring, Stiction, Actuators, Stiction Detection.

1. INTRODUCTION

Control loop performance monitoring is certainly a topics of large interest in research activity and in industrial applications. The possibility of assessing how the plant is behaving is of great importance, both for off-line analysis and for on-line application; the last is the the more challenging task because analysis technique must cope with constraints deriving from real time optimization tools. State of the art, with indications of most advanced fields of application, as well as of several aspects still unresolved in a systematic way, can be found in (Thornhill and Seborg, 2002).

Among different causes which can bring the controlled system to a non optimal behavior can be mentioned: wrong design or tuning of controllers (Ender, 1993), anomalies and failures of sensors, presence of friction in actuators, external perturbations. No doubts that the most popular problems addressed up to date is the uncorrect tuning of controllers, caused by initial errors (too prudential tuning) or by changes in process parameters (due to variations of operating conditions). Automatic techniques for rapid process identification and retuning of industrial controllers have been presented and nowadays find large applications in industry (see (Yu, 1999) for a review of autotuning methods).

One of most common cause of low performance of controlled loops can be found in the presence of stiction in actuators; this fact causes a delayed and sluggish actuation on the process of changes in manipulated variables, required by the control system (Hägglund, 2002). Usually the presence of friction in actuators shows up as oscillations in loop variables (output, manipulated and control signals). Oscillations can be also associated to aggressive tuning (close to marginal stability conditions) or to the inlet of periodic perturbations in the control loop.

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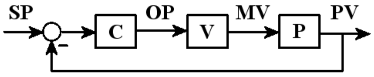

Figure 1. The reference scheme for the controlled loop

A desirable features of a monitoring system is certainly the detection of causes of oscillations, because actions to be taken will be different in the three cases: retuning of controllers, maintainance or substitution of valves, operations in upstream equipments in the plant. Therefore an automatic procedure to detect friction in actuators is called for; several techniques have been presented in literature and find applications in process industry: some of them (Hägglund, 1995), (Taha *et al.*, 1996), are not suitable for automatic implementation, while others can be (Horch, 1999), (Horch, 2000) and have been considered in this study.

After this synthetic introduction to the general problem, the paper reviews basic aspects of stiction, models to describe the phenomenon and techniques for its detection (section 2); applications of the (Horch, 1999) technique to plant data and simulation to different cases are presented in section 3; a new technique is proposed in section 4; a comparison of results from the application to the same cases is reported in section 5; conclusions and further work in section 6.

2. THE PROBLEM OF STICTION

2.1 Monitoring the presence of stiction

The basic control system is depicted in Figure 1, where SP, OP, MV, PV, represent set point, control signal, manipulated and controlled variables. Usually SP, OP, PV are recorded by the DCS, while the manipulated variable MV, which would allow a direct test for the presence of stiction by comparing MV and OP, is not available in the general industrial situation. In our case, the technique to detect the presence of stiction in the actuator is included in a general monitoring system (Rossi *et al.*, 2003), which performs a continuous analysis of data recorded by the DCS; the presence of significant perturbations is detected by the application of Hägglund indexes (Hägglund, 1995), (Hägglund, 1999). The cause of scarce performance must be determined (stiction, inadequate tuning or external perturbation), in order to decide the right operation to be performed on the plant. It is important that stiction is detected automatically, with very low margin of error or uncertainty, reducing to a minimum the need of interaction with operator.

2.2 Stiction Models

The presence of increasing stiction in the actuator introduces a delay and a non linear behavior between the control signal OP and the manipulated variable MV. Referring to Fig. 2: the valve do not move until the active force (F_a) is less than the static friction force (F_s); the integral action of the controller increases F_a over F_s: at this point the valve move and jumps to

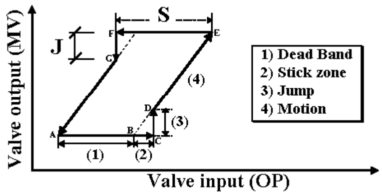

Figure 2. Characteristic Curve of the valve in the presence of stiction

a new position; the net force acting on the stem is always less than the nominal value corresponding to the control action, owing to the presence of dynamic friction (F_d) which depends on the velocity; finally the valve stops again when F_a becomes less than F_s. As a consequence of this phenomenon in the valve (stick-slip), characteristic oscillations appear in the output variable.

Many models have been proposed in literature to describe the presence of friction in the actuators; a survey is reported in (Armstrong-Hélouvry *et al.*, 1994). One of simplest and universally accepted models, is the Karnopp model:

$$m \cdot \frac{d^2x}{dt^2} = F_a - F - F_k \qquad (1)$$

$$F = \begin{cases} -F_d sign(v) + F_v v & if \quad v < -\Delta V \\ max[-F_s, F_a] & if \quad -\Delta V < v < 0 \\ min[-F_s, F_a] & if \quad 0 > v > \Delta V \\ F_d sign(v) + F_v & if \quad v > \Delta V \end{cases} \qquad (2)$$

The active force F_a generated by the controller is balanced by the friction force F and by the spring force F_k. The friction force is the sum of static and dynamic friction. The presence of static friction (that is not a function of v) is showed when valve velocity is $|v| < \Delta V$. Out of this range there is only the dynamic friction force (function of v).

Even though the number of parameters is not large, compared with other models, the lack of knowledge on values of key variables makes the model difficult to implement in a real plant. An alternative approach has been presented recently by (Choudhury *et al.*, 2003). By means of only two parameters (S and J in fig. 2) the model is able to describe characteristic curves of valves in the presence of friction phenomena: S is the range of OP values in which the valve is blocked owing to static friction, J represents the jump obtained when the valve starts to move.

2.3 Techniques for automatic detection of stiction

Several different techniques for detection of stiction have been proposed in literature. Unfortunately, some of them are manual or require strong interaction with the operator (Hägglund, 1995); other techniques require specific knowledge on process and actuators, usually not available (Taha *et al.*, 1996). These have not been taken into consideration in this study oriented towards automatic techniques, without any a priori specific knowledge about the system. The technique proposed by (Horch, 1999), is suitable for automatic

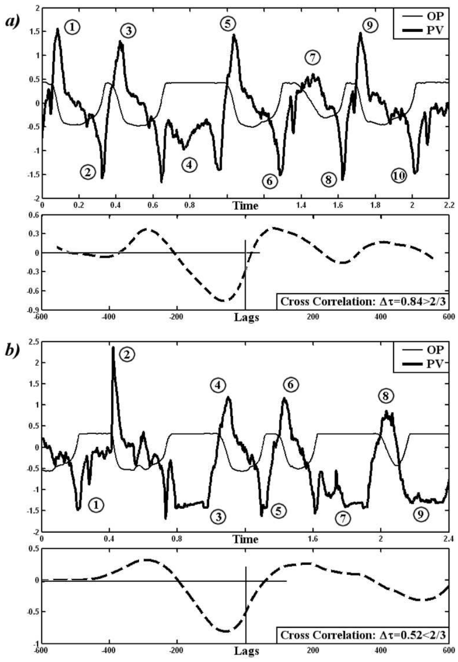

Figure 3. Application of the Horch technique on plant data. a) First set: detection of stiction, b) Second set: uncertainty

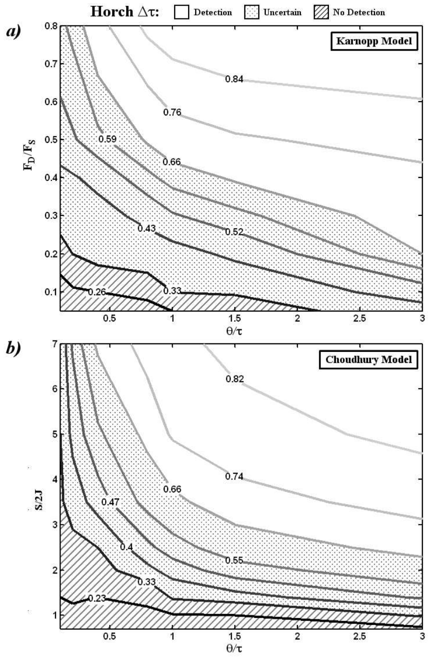

Figure 4. Application of Horch technique; a): Karnopp model, b): Choudhury model

implementation and has been considered for adoption in the monitoring system. From the analysis of different plant data Horch observed that, in the presence of stiction, the control signal OP and the controlled variable PV, oscillate with a phase shift $\phi = \pi/2$, while in the presence of a sinusoidal perturbation the phase shift $\phi = \pi$. This observation has been theoretically explained and a first method based on the Cross-Correlation (C_{XY}) between *OP* and *PV* proposed: in the presence of stiction C_{XY} is an odd function ($\phi = \pi/2$), while in the presence of oscillating disturbances C_{XY} is an even function ($\phi = \pi$). This allows an automatic detection of the two cases, through the computation of two parameters:

$$\Delta\tau = \frac{|\tau_I - \tau S|}{\tau_I + \tau S}; \qquad \Delta\rho = \frac{|r_0 - r_{Max}|}{r_0 + r_{Max}} \tag{3}$$

τ_I e τ_S can be obtained as the two abscissas, closest to zero, where $C_{XY} = 0$; r_0 is the value of C_{XY} in zero and r_{Max} is the maximum value of C_{XY}. According to the values of these two parameters, conditions corresponding to the presence of stiction or sinusoidal perturbations can be indicated; also an uncertainty range, where no decision can be taken, is encountered (gray zone). In details:

$$\left.\begin{array}{l} 0 < \Delta\rho \leq 0.072 \\ 0 < \Delta\tau \leq 1/3 \end{array}\right\} \Rightarrow \mathit{No} \quad \mathit{Stiction} \tag{4}$$

$$\left.\begin{array}{l} 0.072 < \Delta\rho \leq 1/3 \\ 0 < \Delta\tau \leq 2/3 \end{array}\right\} \Rightarrow \mathit{No} \quad \mathit{Decision} \tag{5}$$

$$\left.\begin{array}{l} 1/3 < \Delta\rho \leq 1 \\ 2/3 < \Delta\tau \leq 1 \end{array}\right\} \Rightarrow \mathit{Stiction} \tag{6}$$

A second technique proposed by (Horch, 2000) should also be mentioned; the second derivative of the variable PV is analyzed and its sampling histogram is computed. In the presence of stiction the histogram has a *gaussian* trend; with an oscillating disturbance it has a *bimodal* trend. The technique may be difficult to implement in an industrial environment, because the second derivative can be too sensitive to the typology of noise; for this reason has not been taken into consideration in the present study.

3. APPLICATION OF THE DETECTION TECHNIQUE

3.1 Plant Data

The previously described technique has been applied on plant data obtained from one of the loops of a refinery industry. Examined data refer to a flow control loop, with evident presence of valve stiction and oscillation in controlled output PV. In Fig. 3, sets of recorded data in two different time windows are shown; in the upper part of the figure PV (thick line) and OP (thin line) are reported; in the lower part C_{XY} (dash line) between OP and PV is presented.

In the examined control loop Horch technique was applied choosing a variable number of oscillation with different time windows. The number of analysed oscillations seems not to influence the result and in most cases stiction is correctly detected ($\Delta\tau = 0.7 \div 0.85$); (recorded data and cross correlation showed in Fig. 3a). Using a different time window, again with a variable number of oscillations, results change and lie in the gray-zone ($\Delta\tau = 0.5 \div 0.6$), where no decision can be taken; (recorded data and cross correlation showed in Fig. 3b). Therefore it is important to realise why the presence of stiction can be masked and not detected by the technique. This objective has been addressed by analysing what happens for different extent of stiction and different process dynamics.

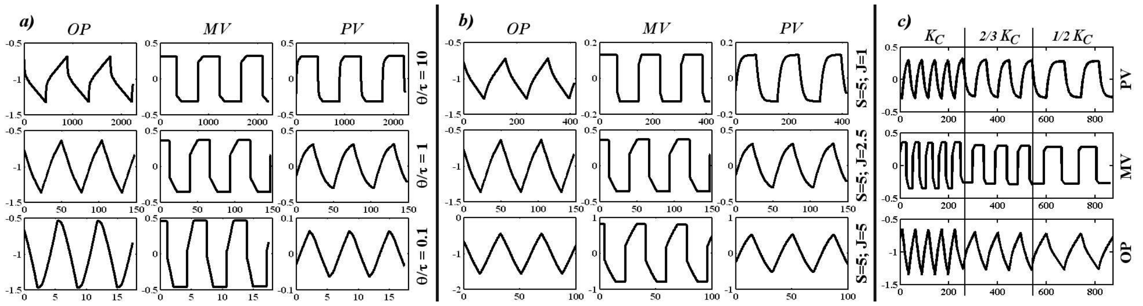

Figure 5. Wave shapes of OP, MV, PV in case of stiction by varying the system parameter: a) variations of θ/τ; b) variations of S/J; c) variations of the controller gain K_C

3.2 Simulation of different cases

To investigate previous point, Horch technique has been applied to situations of presence of stiction generated by two different stiction models (Karnopp and Choudury) for a first order plus time delay process dynamics. Results are reported in Figure 4a and 4b, expressed in terms of the index $\Delta\tau$; (analogous results can be obtained using $\Delta\rho$). Stiction parameters are: the ratio between dynamic and static friction (F_D/F_S, for the Karnopp model, Figure 4a) and the ratio between the dead zone and the jump (S/2J, for the Choudury model, Figure 4b). It can be seen that the presence of stiction is clearly indicated only for processes with large values of the ratio θ / τ and for stiction situations represented by large values of F_D/F_S (or S/2J). On the contrary, for smaller values, no decision can be taken or stiction is not indicated, even though it is present; this result does not depend on the adopted stiction model.

In particular, it is important to point out the effect of process dynamics: for low values of θ/τ (lag dominant processes), the presence of stiction can be hidden (or no decision can be taken), whatever the value of the stiction parameters. Therefore a further investigation of the phenomenon is worth, in order to realise how relevant process variables change with stiction and process dynamics and which of their characteristics do not change.

4. NARROWING THE GRAY ZONE

The analysis of stiction characteristics is based on the observation of different oscillations shape of OP, MV and PV variables. The effect of stiction, process and controller parameters is illustrated in Fig. 5. In Fig. 5a) parameters of stiction are fixed (S=5, J=2.5) and the ratio θ/τ is varied from 0.1 to 10; in Fig. 5b) process parameters are fixed (θ/τ=1) and the ratio S/J is varied ($J < S/2$; $J = S/2$; and $J > S/2$); in Fig. 5c) there is only a variation on the controller gain K_C ($\theta/\tau = 1$,$S/2J = 1$). Choudhury model has been adopted for all the simulations.

Main features can be pointed out as follows (further details in (Rossi and Scali, 2004):

(1) The manipulated variable MV maintains always typical square wave components; the almost perfect square wave shape, shown for θ / $\tau >> 1$, can be slightly modified to saw teeth shape, but the discontinuity on the derivative is maintained.
(2) The controlled variable PV, for decreasing values of S/J and θ/τ, changes its shape from square wave to triangular, much closer to a sinusoidal form.
(3) This effect is even more pronounced when higher order processes with underdamped elements are analyzed; (results reported in Figure 5 are for FOPTD dynamics).
(4) The effect of a change in controller parameters has the peculiarity of not influencing the oscillation shape, but affects the oscillation frequency; in Fig. 5c) a decrease of Kc from 1 to 2/3 to 1/2, causes a decrease of oscillation frequency from 0.116, to 0.067 to 0.044.

From points 2 and 3 it is evident that, basing the analysis on values of PV, it will not be always possible to obtain a sharp distinction between different behaviors, especially in the presence of process noise which tends to cover difference in wave shapes.

In a slight different scenario (relay identification for autotuning purposes (Luyben, 2001) and (Thyagarajan and Yu, 2003), wave shape similar to the ones reported in Figure 5 have been observed for output variables from a FOPTD process. The shape of signals is modified by process dynamics: this suggests the basic idea of the technique proposed here. Every significant recorded oscillation is fitted by using three different models: the output response of a first order plus time delay under relay control, a triangular wave and a sine wave.

The comparison of the error between real and fitted data can be used as an index of accuracy of approximation and then as an indication of the behavior observed in the analyzed variable: relay and triangular waves are associated with the presence of stiction, while sinusoidal shape with the presence of external perturbations.

The three approximating curves (respectively C_S for the sinusoidal wave, C_R for the relay wave and C_T for the triangular wave) are:

$$C_S = A_S \cdot sin(\omega_S t + \phi_S) \tag{7}$$

$$C_R = \begin{cases} A_R(1 - e^{-\frac{t-\phi_R}{\tau_R}}) & t \leqslant t_n \\ C_R^n - (A_R - C_R^n)(1 - e^{-\frac{t-t_n}{\tau_R}}) & t > t_n \end{cases} \tag{8}$$

$$C_T = \begin{cases} A_T(m_1 t + q_1) & t \leqslant t_n \\ A_T(m_2 t + (m_1 - m_2)t_n + q_2) & t > t_n \end{cases} \quad (9)$$

where C_R^n is C_R evaluated at $t = t_n$. There are three typologies of parameters: a parameter $n \in \mathbb{N}$; the parameters $\rho_{NL} = (\omega_S; \phi_S; \tau_R; \phi_R) \in \mathbb{R}$ used in *non linear* functions; the parameters $\rho_L = (A_S; A_R; A_T; m_1; m_2; q_1; q_2) \in \mathbb{R}$ used in a *linear* relation.

Consequentially the parameters are varied on three different levels for each curve: firstly, when requested by the approximating function, n is varied. Secondly, for each fixed value $\overline{n}$, ρ_{NL} parameters are varied with a non-linear optimization (using the *"fminsearch"* function in Matlab). Thirdly, for each fixed set $\overline{\rho_{NL}}$ the parameters ρ_L that generate the best-fit are calculated with linear regression techniques. From all the obtained curves the procedure chooses the three ones ($\overline{C_S}$,$\overline{C_R}$,$\overline{C_T}$) that generate the best-fit with smallest error.

5. RESULTS

5.1 Application on Simulations

The proposed technique has been tested on simulation in closed loop processes (PI-controllers, with Ziegler-Nichols tuning) and in the presence of stiction on the valve, by adopting Choudhury model. Process parameters (θ, τ) and friction parameters (S, J) are varied in the same range chosen for previous analysis (Fig. 4b), for a faster comparison of the old and new gray zones. Indicating with E_Sin, E_Rel and E_Tri respectively the mean square error between the curves C_S, C_R, C_T and the recorded data, two errors can be defined:

$$E_1 \triangleq min[E\_Rel, E\_Tri] \quad (10)$$

$$E_2 \triangleq E\_Sin \quad (11)$$

In the nominal case (no noise) it would be sufficient to impose $E_1 < E_2$. The presence of noise modifies the shape of oscillations and it can be possible to approximate sinusoidal waves with triangular waves (comparable errors); that would generate a false alarm, indicating stiction when it is not present. To avoid this problem, the proposed criterion becomes:

$$E_1 < E_2 \cdot K, \qquad with\, K < 1 \quad (12)$$

A suitable choice for the parameter K, in analogy with the parameter $\Delta\tau$ proposed by Horch, can be: $K = 2/3$. When this criterion is not satisfied, no decision can be taken on the basis of a simple analysis of recorded data, thus generating, unavoidably, a new gray zone. The study about the effect of the noise and overlapped disturbances is still in progress.

The application of the proposed technique, with the suggested criterion, brought results represented in Fig. 6. A logarithmic scale has been adopted for the x axis, in order to zoom in the low values range. It can be observed that a small zone gray zone remains for lag dominant processes ($\theta/\tau < 0.2$): in this range it is not possible to take any decision, also with the new technique; by a comparison with Fig. 4b, the extent of the new gray zone is strongly reduced. Therefore, without any additional knowledge about plant dynamics, it is not possible to detect the presence of stiction in all possible cases and to distinguish it from the presence of external sinusoidal perturbations.

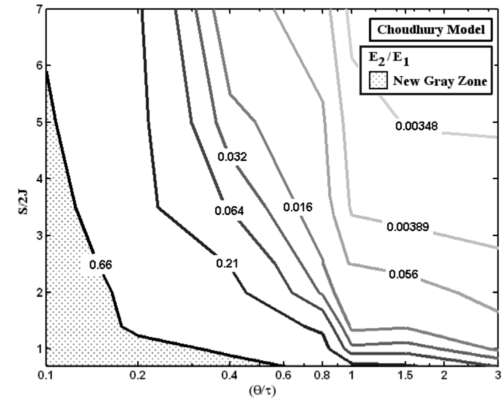

Figure 6. New gray zone with the application of the proposed technique (log x axis)

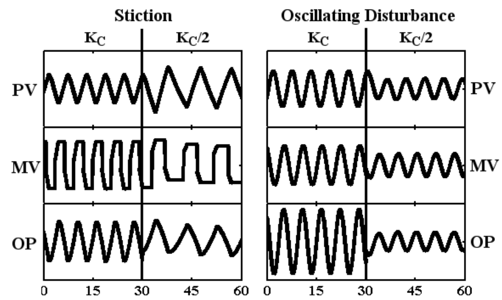

Figure 7. The effect of variations in K_C

Two possibilities are indicated here for a complete detection of stiction.

(1) By recalling that MV in the presence of stiction maintains the typical square wave shape, in the cases that MV is available (recorded by DCS), the gray zone is practically reduced to zero. So, the application of the proposed technique on this variable is able to distinguish correctly the sinusoidal wave (oscillating disturbances) from the square wave or the saw teeth wave (stiction).

(2) When MV is not available (and this is the most frequent situation), cases lying in the gray zone ($E_1 > K \cdot E2$), can be resolved by means of a plant test which decreases the controller gain K_C. In the case of oscillating disturbances, the frequency of the oscillation does not vary (the controller parameters influence only amplitude and phase). In the case of stiction, decreasing K_C causes a significant decrease in the frequency of the recorded oscillation. An example is reported in Fig. 7; this process has $\theta/\tau = 0.1$, so both the technique of Horch and the proposed techniques are in the gray zone. In case of stiction, when the controller gain decreases, also the oscillation frequency decreases ($\omega_1 = 1.25 \rightarrow \omega_2 = 0.68$), on the contrary, with oscillating disturbances it remains constant.

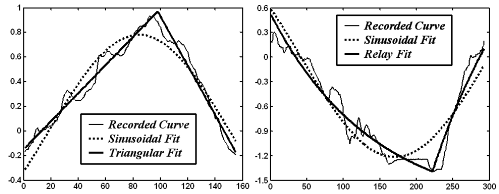

Figure 8. Example of applications on plant data

5.2 Application on plant data

The proposed technique has been applied on the same set of plant data, where the presence of stiction was known. Due to the presence of plant noise, oscillations can show some differences each other, so the technique has been applied on a minimum number of oscillations N_{OSC} equal to 5. The mean error obtained by the three approximating curves for the examined oscillations has been used to discriminate. The total number of oscillations (18) has been examined: values of the ratio $\overline{E_1}/\overline{E_2}$ are reported in Tab.1. It can be seen that for all the examined cases and chosen time windows, this ratio is always less than 2/3, to indicate the presence of stiction correctly. An example of the obtained best-fit for two different oscillations is showed in Fig. 8.

Table 1. Analysis of Plant Data

	$N_{Osc}=6$	$N_{Osc}=12$	$N_{Osc}=18$
I set	0.46	0.50	0.46
II set	0.54	0.49	—
III set	0.39	0.46	—

6. CONCLUSIONS

The analysis carried out in this paper, about the influence of process dynamics and stiction parameters on the characteristics of the output variable (PV), puts into clear evidence that there is a continuous variations of basic properties of oscillating signals. Therefore the presence of stiction can be hidden according to process dynamics and no techniques for automatic detection of stiction can be successful in all possible cases, without any additional knowledge on the process.

These conclusions can be drawn from the application of Horch technique to plant data: stiction is not detected in some cases and simulation results show that there is a large gray zone, where no decision can be made.

The new proposed technique is originated by observing shapes of oscillation in the presence of stiction and compares errors obtained by means of different fitting curves on real data. Even though it is not able to detect stiction in all the cases, by the analysis of PV data only, it allows a significant reduction of gray zones. This is confirmed by the analysis of simulation results and application on plant data. The possibility of analyzing MV data would result in completely successful application; in the cases where no decision can be taken, it is suggest to perform a test on the plant, by decreasing the controller gain.

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