A Novel Approach for Detection of Valve Stiction by Time Delay Estimation

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***Abstract*– The Process variable oscillations in a control loop occur due to poor controller tuning, control valve stiction and oscillatory disturbance. Their effects propagate to control loop and may impact the overall process performance. The high static friction i.e. stiction occurring in a control valve can severely affect the control loop performance. The stiction detection is an important process in a control loop performance monitoring. The objective of this work is detection of oscillations in a control loop, which will identify the result of control valve stiction. The proposed stiction detection method is based on the time delay estimation between manipulated variable and controller output. The selected method has been implemented in the first order plus dead time (FOPDT) process using Matlab.**

Keywords - Control Loop Performance Monitoring; Valve Stiction; Detection of Nonlinearity in Control Loop

I. INTRODUCTION

In recent years there has been an increasing research activity in the area of control loop performance monitoring tool (CLPM). In [1], it is reported that control loop monitoring can be used to improve the performance in an industry. The aim of CLPM tool is to detect deterioration such as increased variability, oscillating behaviour and saturation or offset [2]. The presence of nonlinearity in a control loop, the process variable oscillates around the set point. Oscillations occurred in a feedback control loop are due to poor controller tuning, control valve stiction, and oscillatory disturbance [3]. Choudhury *et al*. [4] indicated that, the control loop performance is very important to ensure tight product quality of low cost product in the process industry. In [5], it is presented the finding and fixing problem loops throughout, plant shows reduced off-grade production, reduced product property variability, occasionally lower operating costs and improved production rate. A survey [6] reported that, even 1% improvement either in energy efficiency or controller maintenance direction leads to hundreds of millions of cost saving to process industries. In [7], concluded that about 30% of the control loops are oscillatory due to control valve problems. A literature survey [8], briefly discussed about the various problems associated with the control valve. The only moving part in a control loop is the control valve. If the control valve contains nonlinearities, e.g., stiction, backlash and deadband, the valve output may be oscillatory, which in turn can cause oscillations in the process output. Among the many type of nonlinearities in control valve, stiction is the most common and one of the long-standing problems in the process industry.

The definition of the term ‘‘stiction’’ is derived by many of the authors/organizations and is given in [9], [10], [11] and [12]. According to Choudhury *et al*. [8], ‘‘Stiction is a property of an element such that its smooth movement in response to a varying input is preceded by a sudden abrupt jump called the slip-jump. Slip-jump is expressed as a percentage of the output span. Its origin in a mechanical system is static friction which exceeds the friction during smooth movement’’. Therefore, identification of oscillations in a control loop is very much essential. Many literatures [13], [14], [15], [16] and [17] have been carried out to define and detect static friction or stiction. The control loop contains non-linearity in a control valve; the process variable is oscillating around set point. Due to that oscillations the time delay is being introduced between controller output and manipulated variable. This paper proposed a novel approach for estimating the time delay which in turn happens in a valve non-linearity. The proposed technique was done by analyzing the estimates of the method from extensive simulated data in closed loop. Valve stiction model is not directly available; hence we simulate the valve stiction model.

This paper is organized as follows. The physical model of valve stiction is presented in section II. The simulation responses of tightly tuned controller, valve stiction and oscillatory disturbance in a control loop are discussed in the section III. The detection of stiction in a control loop using time delay estimation methods are discussed in section IV and the simulation results are presented in section V. Finally conclusion is given in section VI.

II. PHYSICAL MODEL OF VALVE STICTION

Choudhury *et al.* discussed a formal definition for stiction and developed a physical model for valve stiction. Simulating a model using a physical law gives fundamental insights into the effects of friction on a control loop containing a sticking valve. For a pneumatic sliding stem valve, the force balance equation based on Newton’s second law can be written as,

$$M\ \frac{d^2x}{dt^2} = \sum Forces = F_a + F_r + F_f + F_p + F_i \qquad (1)$$

Where M is the mass of the moving parts, x is the relative stem position, $F_a = Au$ is the force applied by pneumatic actuator. Where, A is the area of the diaphragm and u is the actuator air pressure or the valve input signal. The force

$F_r = -kx$ is the spring force, where k is the spring constant and F_f is the friction force, which is given by,

$$F_f = \begin{cases} -F_c \,\mathrm{sgn}(v) - vF_v & \text{if } v \neq 0, \\ -(F_a + F_r) & \text{if } v = 0 \text{ and } |F_a + F_r| \le F_s, \\ -F_s \,\mathrm{sgn}(F_a + F_r) & \text{if } v = 0 \text{ and } |F_a + F_r| > F_s. \end{cases} \quad (2)$$

The force F_p is a force due to fluid pressure drop and, F_i is an extra force given to the valve move to seat. For better understanding and convenience to simulate the valve stiction model, these F_p and F_i forces are ignored. The friction model was developed for using the friction force equation, which includes both static and moving friction. The expression for the moving friction is in the first line of Eqn. (2). The second line in Eqn. (2) is the case when the valve is stuck. The third line of the model represents the situation at the instant of breakaway. Thus the simulation model was developed by using the above force balance equation and friction force equations. The nominal values of physical valve are given in Table I [8].

TABLE I NOMINAL VALUES FOR SIMULATION OF PHYSICAL VALVE

Parameters	Nominal valve
M	1.36 kg
F_c	$1250N$
F_v	$612\,N\,s\,m^{-1}$
Spring constant k	$52{,}500\,N\,m^{-1}$
Diaphragm area, A	$0.0645\,m^2$
Calibration factor, k/A	$807{,}692\ Pa\,m^{-1}$
Air pressure	$68{,}950\,Pa$

In the absence of stiction effects, the moving parts of the valve comes to rest when the force due to air pressure on the diaphragm is balanced by the spring force. Thus, $Au = kx$ and so the calibration factor relating to the air pressure u to x_r is k/A. The stiction model is to determine the influence of the three different friction terms that are given in table II. The nonlinearity in the model is capable to induce the limit cycle oscillations in a feedback control loop. The Equations (1), (2) and Tables I, II are used to complete the simulation of valve stiction model.

TABLE II FRICTIONAL VALUES IN CLOSED LOOP SYSTEM

Parameter	Linear	Stiction
$F_s\,(N)$	45	1000
$F_c\,(N)$	45	400
$F_v\,(N\,s\,m^{-1})$	612	612

III. SIMULATION RESULTS FOR OSCILLATIONS IN A CONTROL LOOP

For the assessment of closed-loop behavior, the valve output drive is a first-order plus dead time process $G(s)$ and receive the input signal from PI controller $C(s)$. The process transfer function and controller transfer function are given in Eqn.3.

$$G(s) = \frac{3e^{-10s}}{10s+1}, \qquad C(s) = 0.2\left(\frac{10s+1}{10s}\right) \quad (3)$$

The oscillations in a control loop takes place due to tightly tuned controller, oscillatory disturbance and valve stiction. The above mentioned factors were simulated and their responses are discussed in the following topics.

A. *Closed Loop Response of PI Controller with FOPDT Process*

The control loop accepts the set point (SP) and the measured variable (PV) as its input and compute a control signal (CO) using PI type control law. The simulation of the FOPDT process with PI controller responses is shown in Fig.1 to Fig. 3. The responses are taken under the condition of linear characteristics of valve and the absence of improper tuning of controller and oscillatory disturbance.

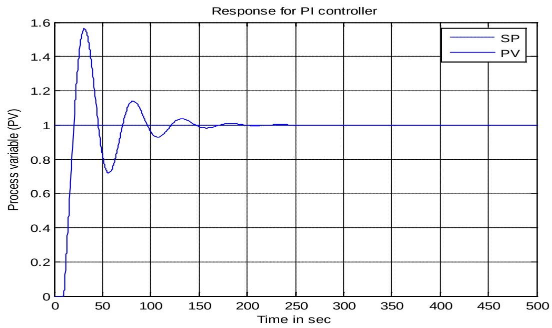

Fig. 1 Servo response with PI controller

The servo response of the system to a unit step change is shown in Fig. 1. From the response, it is clear that feedback closed loop system is not having any oscillations.

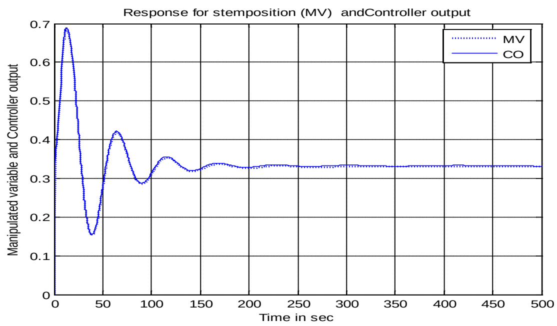

Fig. 2 Response for stem position and controller output

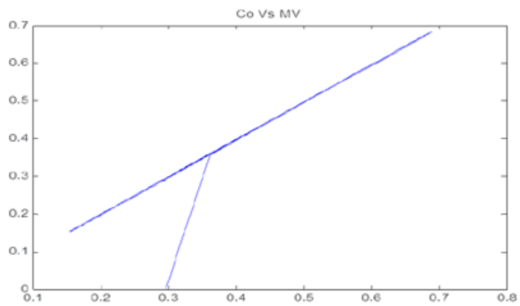

Fig. 3 Plot for Manipulated variable Vs Controller output

Fig. 2 shows the simulated response for stem position and controller output. From the response observed, time delay is not present. A plot for manipulated variable versus controller output is shown in Fig. 3, this plot shows the characteristics of linear valve. The comparisons of the above responses are given in table III.

TABLE III COMPARISON OF RESPONSES FOR LINEAR VALVE

S.No	Responses	Remarks
1	Servo response	Oscillations are not available
2	Stem position and controller output	Time delay is not observed in between stem position and controller output
3	Controller output Vs Manipulated variable	Observed the linear characteristics of valve

B. *Closed loop response for PI controller with improper controller tuning*

The simulation of FOPDT process with tightly tuned PI type controller and simulated response is shown in Fig.4 to Fig. 6. These responses are taken under the absence of valve stiction model and external oscillatory disturbance.

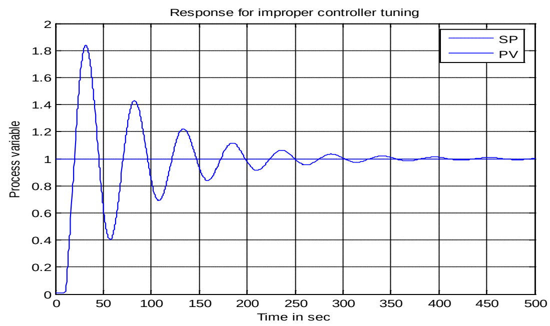

Fig. 4 Servo response with tightly tuned controller

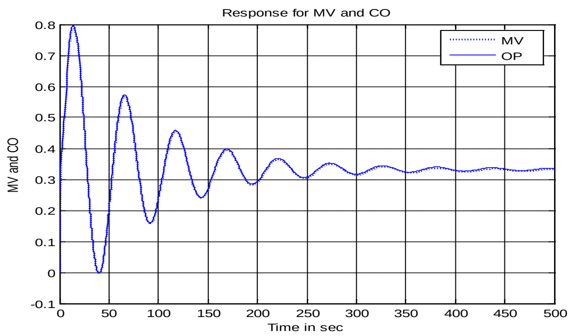

Fig. 5 Response for stem position and controller output

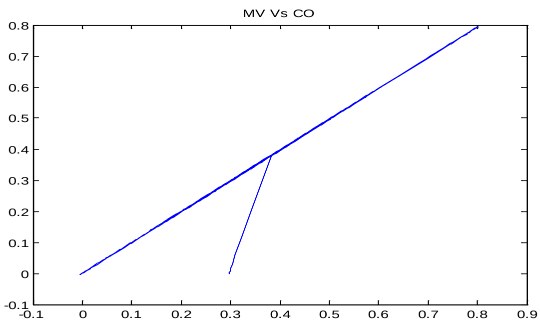

Fig. 6 Plot for Manipulated variable Vs Controller output

The servo response of the system is oscillatory for unit step change and is shown in Fig. 4. From Fig. 5, it is clear we have not observed the time delay between manipulated variable and controller output. The linear characteristic of valve is identified from the Fig.6. These responses are taken under the presence of tightly tuned controller and the comparisons of above responses are summarized in table IV.

C. *Closed Loop Response for PI Controller with Oscillatory Disturbance*

The simulation FOPDT process with well tuned PI type controller and simulated response are shown from Fig. 7 to Fig. 9. These responses of a closed loop system are taken under the presence of external oscillatory disturbance and the absence of valve stiction model.

TABLE IV COMPARISON OF RESPONSES FOR TIGHTLY TUNED CONTROLLER

S.No	Responses	Remarks
1	Servo response	Oscillations are available
2	Stem position and controller output	Time delay is not observed in between stem position and controller output
3	Controller output Vs Manipulated variable	Observed the linear characteristics of valve

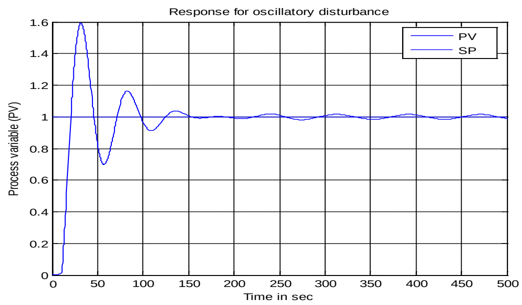

Fig. 7 Servo response with oscillatory disturbance

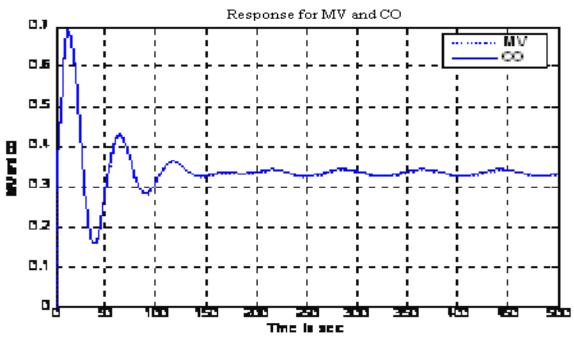

Fig. 8 Response for stem position and controller output

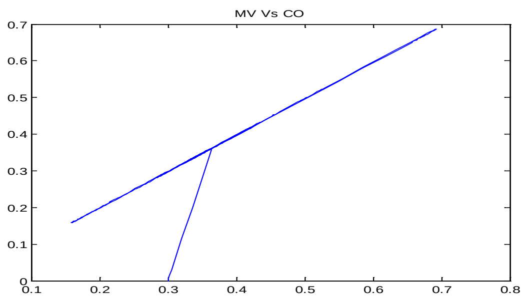

Fig. 9 Plot for Controller output Vs Process variable.

The servo response of the system is oscillatory for unit step change shown in Fig. 7. From Fig. 8, we observe that there is no time delay between stem position and controller output and the plot Fig. 9 shows, the linear characteristics of valve. The above responses were carried out in the absence of improper tuned controller and valve stiction. The comparisons of the above responses are given in table V.

TABLE V COMPARISON OF RESPONSES FOR OSCILLATORY DISTURBANCE

S.No	Responses	Remarks
1	Servo response	Oscillations are available
2	Stem position and controller output	Time delay is not observed in between stem position and controller output
3	Controller output Vs Manipulated variable	Observe the linear characteristics of valve

D. Closed Loop Response for PI Controller with Stiction

The closed loop FOPDT process with proper tuned PI controller and the simulated responses are shown in Fig. 10 to Fig. 11. These simulated responses were taken under the presence of valve stiction model and the absence of external oscillatory disturbance. The servo response of the closed loop system is oscillatory for unit step change and is shown in Fig. 10. From Fig. 11,the response of manipulated variable and controller output, it is clear that it has time delay and also inferred that from feedback closed loop system that it has stiction. By using Fig. 12, we have identified the definition of stiction [8]. It is possible to identify the stiction inside the control loop and the plot for process variable versus controller output will form an ellipse as shown in Fig.13. The comparisons of the above responses are given in Table VI.

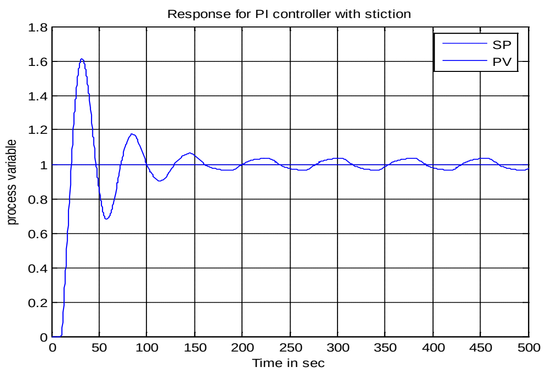

Fig.10 Servo response with oscillatory disturbance

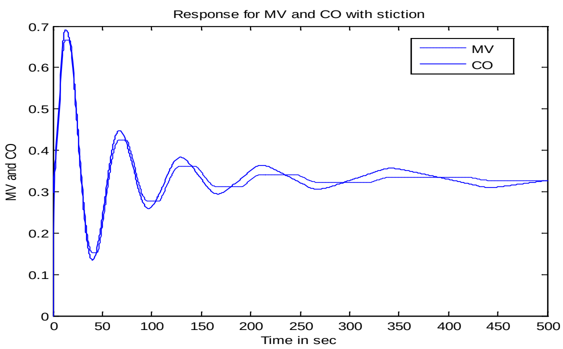

Fig.11 Response for stem position and controller output

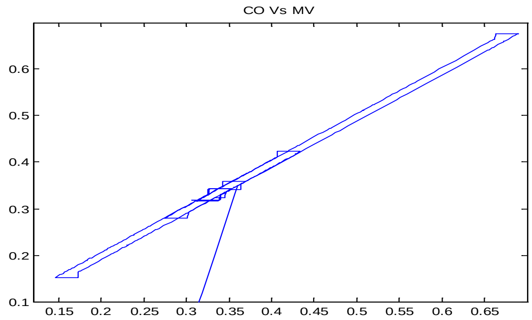

Fig.12 Plot for Controller output Vs Manipulated variable.

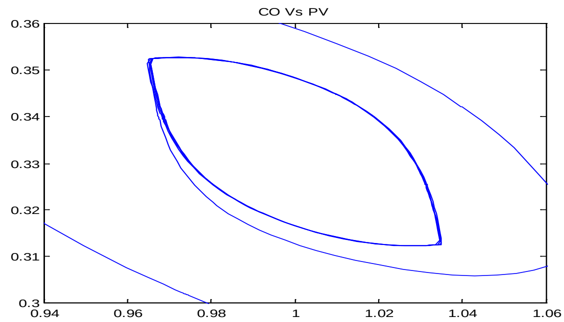

Fig.13 Plot for Controller output Vs Process variable.

TABLE VI COMPARISON OF RESPONSES FOR VALVE STICTION

S.No	Responses	Remarks
1	Servo response	Oscillations are available
2	Stem position and controller output	Time delay is observed in between stem position and controller output
3	Controller output Vs Manipulated variable	Observed the non linear characteristics of valve
4	Controller output Vs Process variable	Observed the ellipse formation

From the discussions in subheadings A,B,C and D, it is clear that, valve stiction in a feedback closed loop system is easily identified by the time delay between manipulated variable and controller output.

IV. DETECTION OF STICTION USING TIME-DELAY ESTIMATION

The control loop performance monitoring has received much attention in the field of engineering research. If there are some nonlinearities in the control loop, the controller may not perform at the desired level. Choudhury et al [4], discussed briefly about the classical signal processing tools such as power spectrum that utilize only the first and second order moments, i.e., the mean and covariance. Such a tool is mainly useful for analyzing signals from linear process. Many literatures [4], [18], [19] and [20] have discussed the necessity of the use of nonlinear signals, one needs to look at other methods of characterizing their statistical properties. The [18] and [21] reported that the necessity of the use of higher-order statistical tools. The third- and fourth-order moments or cumulants and their frequency domain counterparts are found to be useful in analyzing nonlinearities in communication signals, radar signals, nonlinear ocean wave analysis, seismic signal analysis, speech signal analysis and mechanical machine condition monitoring. Choudhury et al briefly reported that the higher order statistics (HOS) tools have been widely used in the above mentioned areas, they have been used in solving problems in process control. HOS tools such as cumulants, bispectrum and bicoherence will develop two new indices: the Non-Gaussianity index (NGI) and the Nonlinearity index (NLI) for detecting and quantifying non-Gaussianity and nonlinearity that may be present in regulated systems, and to use routine operating data to diagnose the source of nonlinearity. This paper introduced time delay estimation in HOS tool and showed the potentials of using these tools in control loop performance analysis. The time-delay estimation problem occurs in various applications, for example, determination of range and bearing in radar and sonar. It also has process control applications, such as the measurement of temperature of a molten alloy by measuring the passage time of a signal. Other applications include analysis of EEG data [21]. The time delay between controller output and manipulated variable is due to the control loop contained nonlinearity i.e. stiction.

The basic equation is as follows: two measured delayed replicas of a signal, in the presence of noise:

$$x(t) = s(t) + w_x(t)$$
$$y(t) = As(t-D) + w_x(t) \tag{4}$$

Where, *D* is the delay of the signal at the *y* is measured signal at the *x*- signal, *A* is the relative amplitude gain and $w_x(t)$ is the sensor noise. For given *x* (*t*), *y* (*t*), t=0…… *N* – 1, we want to estimate the delay *D*. The basic idea is to shift the signal *y* (*t*) and compare the shifted waveform with *x*(*t*); the best match occurs when the shift equals the delay *D*. We assume that *s*(*t*) is a stationary process, and that the noises are at zero mean.

A. Cross-Correlation Based Method

The cross-correlation between the two signals *x*(*t*) and *y*(*t*) is given in Eqn.5. Here the sensor noise is ignored.

$$R_{xy}(\tau) = AR_{ss}(\tau - D) \tag{5}$$

Where, $R_{ss}(\tau)$ is the autocorrelation of the signal. If the signals are uncorrelated, $R_{xy}(\tau)$ will have a peak at $\tau = D$, the unknown delay. In practice, due to effects of finite length estimates, and due to the presence of noise, the cross-correlation estimate may not have a sharp peak. The data may be prefiltered in order to sharpen the peak; equivalently, we can multiply the estimated cross-correlation by a window function. Different choices of the window function lead to different estimates. The most popular window function is the maximum-likelihood window of Hannan and Thompson, which is described below [21].

Let $S_{xy}(f)$ denote the cross-spectrum between the two signals, *x* and *y*; and let $S_{xx}(f)$ and $S_{yy}(f)$ denote the auto spectra of *x* and *y*. The squared coherence function is defined by,

$$C_{xy}(f) = \frac{\left|S_{xy}(f)\right|^2}{S_{xx}(f)S_{xx}(f)} \tag{6}$$

The optimal-maximum-likelihood window is then

$$W(f) = \frac{1}{\left|S_{xx}(f)\right|}\frac{C_{xy}(f)}{(1-C_{xy}(f))} \tag{7}$$

And the cross-correlation, $R_{xy}(m)$, is the IFT of $W(f)$ $S_{xx}(f)$. Estimates of the auto- and cross- spectra and the coherence can be obtained via the MATLAB routine spectrum; the segment length must be at least twice in the expected maximum delay. Since good estimates of the spectra demand a large number of segments, it is critical that the lengths of the time-series, *x* and *y*, be much larger than the expected maximum delay.

An initial estimate *d*, of the delay *D* is given by the location of the peak of $R(m)$. A three-point interpolation may be used to improve the delay estimate.

$$\hat{D} = \frac{2D-1}{2} - \frac{R(d) - R(d-1)}{R(d+1) - 2R(d) + R(d-1)} \tag{8}$$

B. Cross-Cumlant Based Method

The cross-correlation based method assumes that the measured signals are uncorrelated. If the noise processes are correlated, it may not be possible to detect the peak of $R_{ss}(\tau)$. If the signals are non-Gaussian, and the noise processes are Gaussian, we can use third-order cumulants, even if the noise processes are correlated [21].

Let *P* be the maximum expected delay, and assume that the delay *D* is an integer. Then,

$$y(n) = \sum_{i=-P}^{P} a(i)x(n-i) + w(n) \tag{9}$$

Where, $a(n) = 0$, $n \neq D$, and $a(D) = 1$. The sensor noise $w(n)$ is ignored. Consider the third order cumulants,

$$C_{yxx}(\tau,\rho) = \sum_{i=-P}^{P} a(i)C_{xxx}(\tau+i, \rho+i) \tag{10}$$

Using this equation for various values of ρ and τ, we get a system of linear equations in the *a*(*i*) is namely,

$$C_{xxx}a = C_{yxx} \tag{11}$$

The estimated delay is the index n which maximizes |*a*(*n*)|. A low rank approximation of the cumulant matrix C_{xxx} may be used to improve the robustness to noise.

V. SIMULATION RESULTS FOR DETECTION OF STICTION IN A CONTROL LOOP

Due to poor or tightly tuned controllers or due to a linear external oscillatory disturbance or valve stiction will occur oscillations in control loop. In the presence of stiction inside the control loop will occur time delay between manipulated variable and controller output. The proposed method is used to detect stiction in a control loop using time delay estimation between manipulated variable and controller output. The time delay is estimated between the two variables using the Cross correlation based method and Crocess-Cumlant based method. The methods are simulated and the responses are shown in Fig. 14 to Fig. 21.

A. A cross correlation based method

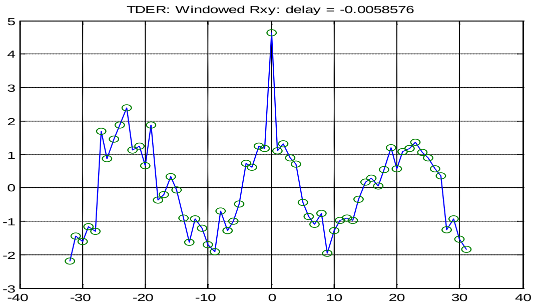

Fig.14 Response for process with PI controller

(valve is linear)

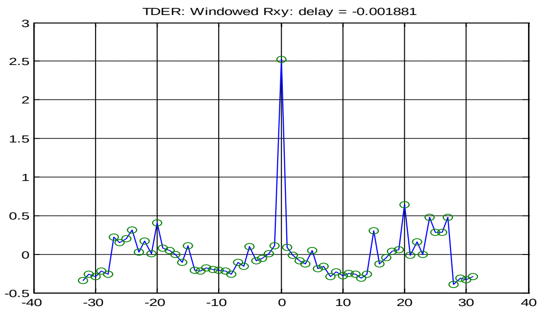

Fig.15 Response for process with tightly tuned controller

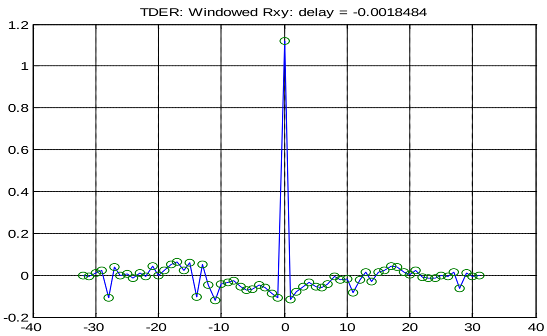

Fig.16 Response for process with oscillatory disturbance

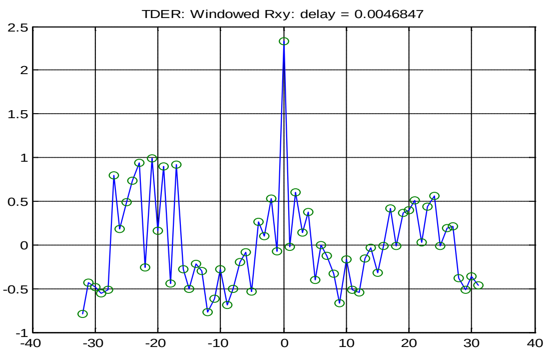

Fig.17 Response for process with presence of stiction

B. A Cross-Cumlant Based Method

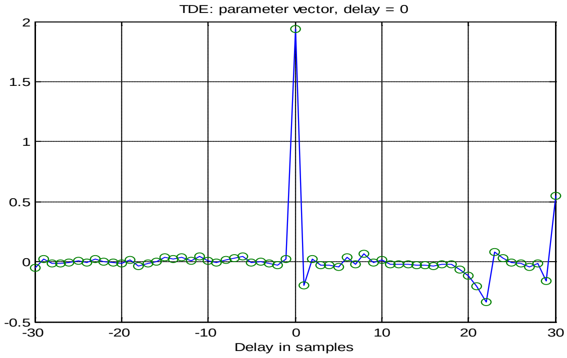

Fig.18 Response for process with PI controller

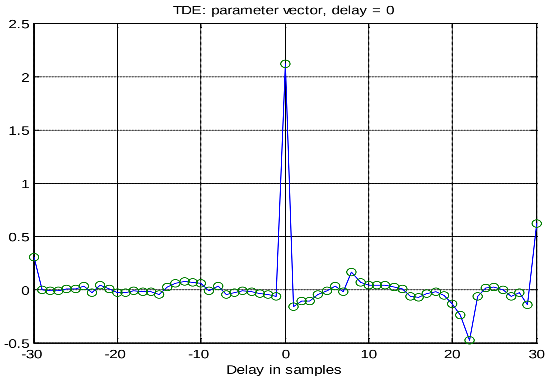

Fig.19 Response for process with tightly tuned controller

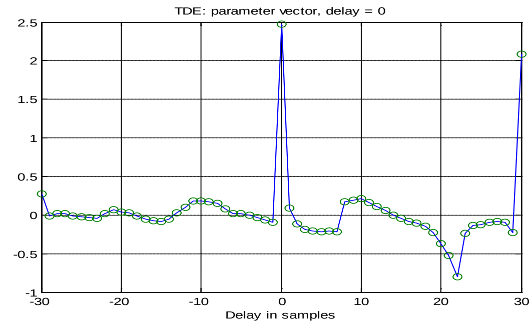

Fig.20 Response for process with oscillatory disturbance

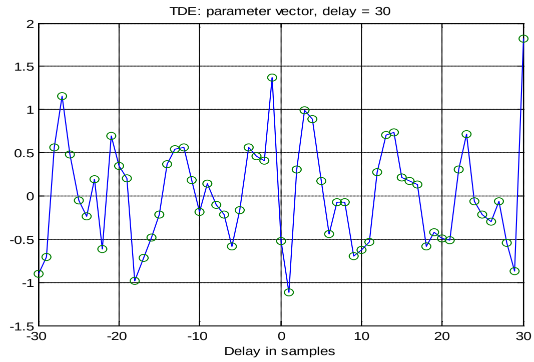

Fig.21 Response for process with presence of stiction

Simulation results are performed by using MATLAB simulink. The proposed Cross correlation and Cross-Cumlant based methods are used to validate their performances. The simulation work for above mentioned methods can be done by using HOSA Toolbox. The simulated responses of both methods are shown in Fig.14 to Fig. 21. They give the values of zero, positive and negative, which is given in table VII.

The PI controller parameters are well tuned for first case and valve stiction model was considered linear in simulation block. Simulation for both the methods were done and obtained responses are shown in Fig. 14 to Fig. 18.The proposed Cross correlation and Cross-Cumlant based method yields a values of -0.0058576 and 0 respectively. This negative and zero values indicate that the control loop is not having any nonlinearity. For the second case the controller parameters were improper tuning. Simulated responses are shown in Fig. 15 and Fig. 20 for both the methods. A Cross correlation based method has a value of -0.001881 and Cross-Cumlant based method have a value of zero. It is clearly indicated that in control loop, oscillations are not due to nonlinearity. A sinusoidal oscillatory disturbance has to be inserted in the third case of the control loop. The simulated responses are shown in Fig. 16 and Fig. 20. The proposed Cross correlation based method gives a value of -0.0018484 and Cross-Cumlant based method gives a value of zero. It is clearly identified that there is no nonlinearity inside the control loop. Choudhury et al., stiction model was used to perform the fourth case. The obtained simulation responses are shown in Fig. 17 and Fig. 21. The proposed Cross correlation based method gives a value of +0.0046847 and Cross-Cumlant based method gives a value of 30. It is clearly identified that the reason for oscillations is valve nonlinearity i.e. stiction. The above mentioned four different cases are used in a oscillatory control loop and the calculated time delay values are given in table VII.

TABLE VII DELAY ESTIMATION VALUES IN CLOSED LOOP SYSTEM

S.No	Factors	Delay estimation method	
		Cross correlation method	**Cross-Cummulant method**
1	Closed loop with PI controller (Case I)	-0.00586	0
2	Oscillatory disturbance (Case II)	-0.00184	0
3	Tightly tuned controller (Case III)	-0.00181	0
4	Valve Stiction (Case IV)	+0.0046	30

A cross-cummulant based method is used to estimate the time delay between manipulated variable and controller output signal. The second method yields a value of zero and positive magnitude values. This positive value indicates the presence of stiction inside the control loop. Thus the proposed methods are used to detect the stiction in a control loop.

VI. CONCLUSIONS

Thus paper identifies the physical valve stiction that is simulated and identified on the various oscillations in control loop due to nonlinearity inside the control loop, in order to enter the oscillatory disturbance and tightly tuned controller. Moreover, this paper presents the selected novel methods for detection of oscillations in control loop. From the approach innovative results and the proposed methods is used to detect the one of the valve nonlinearities i.e., valve stiction inside the control loop.

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