A SIMPLE METHOD FOR COMPENSATING STICTION NONLINEARITY IN OSCILLATING CONTROL LOOPS

Srinivasan Arumugam[*1], Rames C.Panda[#2] and Vijayan Velappan[#3]

[*1]Department of ECE, GKMCET, Chennai- 600 063, India.

[#2]Principal Scientist, Department of Chemical Engineering, CSIR-CLRI, Chennai- 600 020.

[#3]Deparment of EIE, St. Joseph's College of Engineering, Chennai-600 119.

[*1]a.srinivasan2025@gmail.com, [#2]panda@clri.res.in and [#3]vinvpn@gmail.com

Abstract- Stiction in control valves is an extremely nonlinear and one of the long-standing problems in a closed loop control system, since the controller will push the control valve to move until the controlled variable reaches the desired value. Stiction moves the control valves to extreme positions so that the process output will force to produce overshoot. Then, the action gets repeated as the controller output reverses its direction. The limit cycle generated, when the control valve sticks and slips during a change in input signal is called stick/slip cycle, will induce vibrations. As the control loops in an industrial plant are interlinked each other; these oscillations will be propagated to the entire system. In this critical situation the only option is to go for maintenance of the faulty valves, which may be recommended/ possible only during process shut down. But, shutting down the process for maintenance of defective valves is not an economical option. Hence, it is very important to provide an efficient technique to compensate the nonlinear effect of the stiction in faulty control valve, especially when it is not under maintenance. This paper proposes a new compensation approach using sinusoidal signal for the stiction nonlinearity present in such faulty control valves.

Keyword-Nonlinear, Control valve, Stiction, Modelling, Identification, Quantification, Compensation

I. INTRODUCTION

One important moving part in a feedback control loop is the pneumatic control valve. If the control valve contains non-linearities, *e.g.* stiction, backlash, and dead-band, the valve output may be oscillatory that in turn can cause oscillations in the process output. Among the different types of non-linearities in control valves, stiction is the most common and is one of the long-standing problems in the process industry. It hinders the achievement of good performance of control valves as well as control loops. When stiction is present in the control loops, problems like increased energy consumption, deteriorated product quality and excessive wear of the machinery may appear. It is mentioned in [1] that about 20-30% of the oscillations in control loops are caused by stiction, which motivates the importance of this study.

Stiction in control valves is thought to occur due to degradation of seal, depletion of lubricant, inclusion of foreign matter, activation at metal sliding surfaces at high temperatures and tight packing around the stem. The resistance offered from the stem packing is often considered as the main cause of stiction. Another very common cause of stiction is indirectly related to regulations on volatile organic compound emissions. In many plants, a team monitors each valve for emissions of volatile organic compound, usually between the packing and the stem. If any minute leakage is detected, packing in the valve body is tightened far more than is necessary which causes the valve to stick and making the process inefficiently with increased energy consumption. Stiction often varies over time and operating regimes. Since wear is also non-uniform along the body, frictional forces appear to be different at different stem positions [2]. Valves under stiction may give erroneous output that will drift the system to different directions causing deterioration in performance. The actual output from the control valve must be given to the process in order to get desired performance. Thus a sub system needs to be designed to compensate and revise the input to the process. Choudhury[9] presented model based compensation technique to recalculate actual control output. Many researchers Kano [21], He [10], Chen [8] proposed simpler model structure to handle stochastic noise naturally and simulated the sticky-valve behaviour similar to the ones observed in industrial cases.

Non model-based strategies (Hägglund, 2002) exhibit dithering and impulse control. But, this knocker based method requires extra physical forces acting on the control valve. It uses the square waves containing harmonics that causes sudden changes in the manipulated variable which may affect the control valves subsequently. Some methods based on heuristic approaches [43, 44] have been reported for compensating stiction in control valves. But, their works calculate non-optimal controller outputs. Hence, a novel method is proposed in this article to properly compensate stiction in control valves. Thus the rest of the paper is organized as follows: control valve stiction is explained in section II. Section III discusses detection and modelling of control valves. Some of the existing quantification and compensation techniques are discussed in section IV and V. Performances of the without compensation and performances of with compensation using knocker method have been discussed in section VI and VII respectively. The proposed compensation method is presented in section VIII. The results and discussions are discussed in section IX. Conclusions are drawn at the end.

The general block diagram of process control valve (in closed-loop) with stiction is illustrated in Figure 1. In the control loop diagram, 'r' denotes reference input, the controller gain is denoted as G_c, the control valve gain is represented as G_v and the process gain is denoted as G_p. Measurements of the process variable PV and controller output OP were used to estimate the parameters of a Hammerstein system, consisting of a non linear control valve stiction model and a linear process model. The process output is denoted as 'y_b' and the external disturbance is denoted as 'y_d'. Finally, the process variable PV is denoted 'y' and the expression of output is described as follows,

$$y = y_b + y_d = N(u) + y_d \tag{1}$$

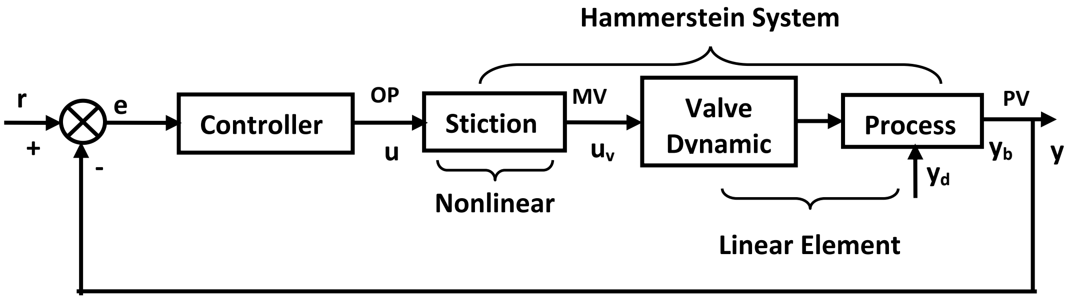


Figure 1. Block Diagram of Closed Loop Process Control System with sticky valve

Where, y_b is the process component in equation (1) in terms of control valve output 'u_v' and process transfer function 'N'. The identification of the linear dynamics (valve&process) is decoupled from the nonlinear element (stiction). The decoupling between the nonlinear and the linear component is achieved by an iterative procedure.

II. CONTROL VALVE STICTION

Different researchers or organizations have defined stiction in different ways. Some of these definitions have been presented in [3]. Based on careful investigation of real process data a new definition of stiction has been proposed by [4] and is summarized as follows. "Stiction is a property of an element such that its smooth movement in response to a varying input is preceded by a static part (dead-band + stick-band) followed by a sudden abrupt jump called '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 dynamic friction during smooth movement". Figure 2 shows the schematic general structure of a pneumatic control valve. In most of the control loops in process industries, pneumatic control valves are used as final control elements. The valve aims to restrict the flow of process fluid through the pipe and the valve plug is rigidly attached to a stem that is attached to a diaphragm in an air-pressure chamber in the actuator section at the top of the valve. When compressed air is applied, the diaphragm moves down and the valve closes to restrict the flow and at the same time, the spring is compressed. Stiction happens when the smooth movement of the valve stem is hindered by excessive static friction at the gland packing section. The sudden slip of the stem after the controller output sufficiently overcomes the static friction caused undesirable effect to the control loop. The resistance offered from the stem packing is often considered as the main cause of stiction.

The study of stiction in the literature can be divided in three main branches and they are 1) Detection and modelling, 2) Quantification and 3) Compensation. The phase plot of the input-output behavior of a valve "suffering from stiction" is described as shown in Figure 3. It consists of four components: dead-band, stick-band, slip jump and the moving phase. When the valve comes to a rest or changes the direction at point A in Figure 3 the valve sticks as it cannot overcome the force due to static friction. After the controller output overcomes the dead-band AB plus the stick-band BC of the valve, the valve jumps to a new position D and continues to move. Due to very low or zero velocity, the valve may stick again in between points D and E while travelling in the same direction. In such a case the magnitude of the dead-band is zero and only the stick-band is present.

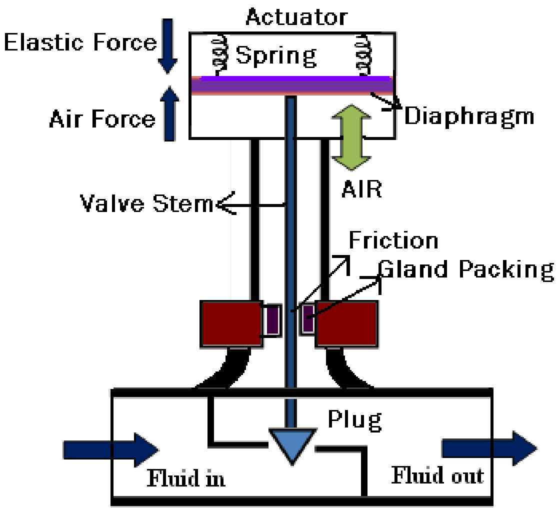


Figure 2. Schematic diagram of a control valve

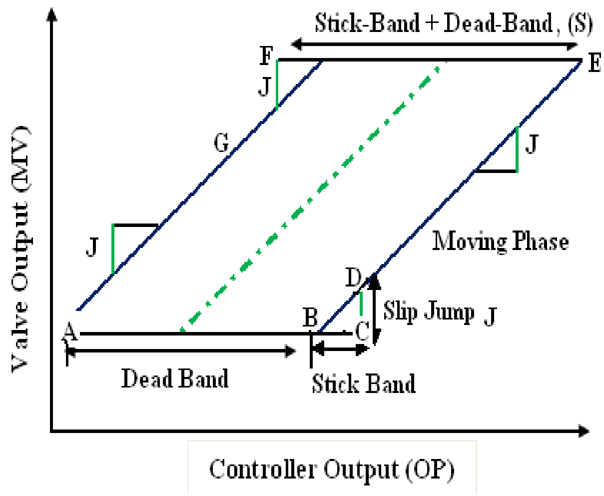


Figure 3. Input-Output behavior of a sticky valve

III. STICTION MODELLING AND DETECTION

Stiction in a control valve appears as a hard nonlinearity in the control loop dynamics. Therefore, in order to detect stiction, the first approach to the problem is detected whether there is nonlinearity in a control loop. If nonlinearity is detected, it should be diagnosed whether it has arisen from valve stiction or for some other reasons. Therefore, the detection of stiction in a control loop involves a two step procedure. i) Detection of loop nonlinearity and ii) Diagnosis of nonlinearity for the presence of stiction.

Modeling can be divided into physical models presented in [5], [6], [7] and empirical/data-driven models presented in [8] and [9]. Comparison of physical models and data-driven models are presented in [12]. A disadvantage of a physical model of a control valve is that it requires several parameters namely the knowledge of the mass of the moving parts of the actuator, spring constant, and the friction forces. To be known, while the data-driven model has parameters that can be directly related to plant data and it produces the same behavior as the physical model. The model needs only an input signal and the specification of dead-band plus stick-band and slip-jump. Some authors propose models that use a single parameter [14] and [15], the other method called two-parameter models are also presented in [8], [10], and [13]. Many studies [16-27] have been conducted to define and detect static friction or stiction.

IV. STICTION QUANTIFICATION

In a Large scale processing plants include hundreds and even thousands of control loops exist. The aim of each control loop is to maintain the process at the desired operating conditions, securely and effectively. There are several methods for detecting stiction as mentioned above, but quantification of the actual amount of stiction still remains a challenging one. Some of them may be sticky by an acceptably small amount for the current application in hand, while others may suffer from severe stiction and need immediate maintenance of the valve. Therefore, it is important to be able to quantify stiction to run a plant in smooth conduction without disturbing the quality of the end product [28-38].

V. STICTION COMPENSATION

Control valve stiction compensation is a broad area of research in the literature. There are three main types of compensation strategies: friction avoidance, non model-based compensation and model-based compensation. The model-based compensation techniques that use coulomb or general friction models and the models are data-driven model, Kano's model [21]; He's model [10] and Chen's model [8]. He's model employs a simpler model structure compared to Choudhury's and Kano's model, this model naturally handles stochastic noise and can simulate the sticky-valve behaviour similar to the ones observed in industrial cases. Examples of non model-based strategies include dithering and impulse control. The most common type in control loops [15] is ineffective for pneumatic valves, because they filter high frequency signals.

An alternative dithering method which is very efficient compensation method is presented in [39] and is called 'the knocker'. This consists of a series of short pulses with constant amplitude, width, and time between each two pulses in the direction of changes in the control output signal. The schematic diagram of a closed loop control scheme containing a compensator is shown in Figure 4. This compensator can successfully minimize the stiction-induced oscillations from the process output. In the two-move approach the compensator first takes the stem to the steady-state value and then a controller is used to prevent from deviating the steady-state value.

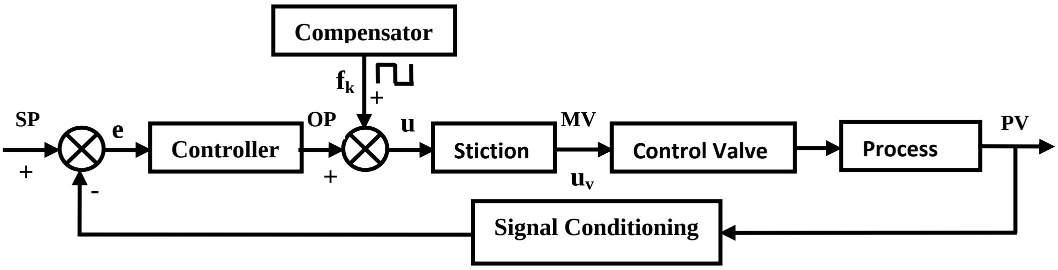


Figure 4. closed loop control system with stiction compensator using knocker pulse

In the closed loop control system with stiction compensator OP represented as controller output, f_k represented as compensator signal, SP represented as process setpoint, PV represented as process output, e represented as the error, u represented as the additive signal (OP + f_k) that is being fed to the valve which is affected by the stiction nonlinearity and u_v represents the stem position. The knocker parameters for 'τ', 'h_k' and 'a' are set to 2h, 5h and d/2 respectively where 'h' is the sampling time and 'd' is the stiction measure, the waveform of knocker pulse is shown in Figure 5.

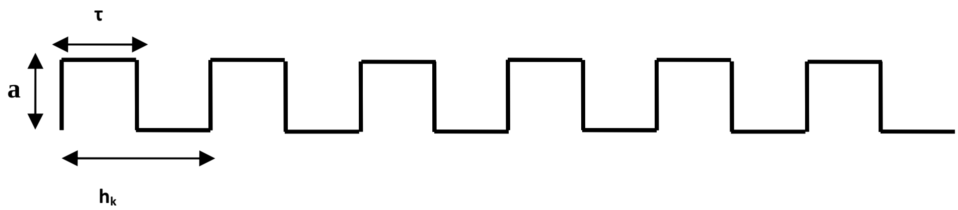


Figure 5. Knocker Pulse (h_k=time interval between the pulses, a= pulse amplitude, τ=pulse width,)

An improved knocker method presented in [40] to calculate the required parameters. He's model in [10] presented with an improved stiction estimation scheme. The compensation is achieved via 'constant reinforcement' approach, which is similar to the knocker, except that the signal added to the control signal is constant. This method is useful only for time intervals when the valve does not move in response to the controller output changes, and generally ignores extra movements. Reference [41] extends the two-moves approach and used a modified PI for processes with constant disturbances. However, this method decreases the accuracy of the end products. Based on the two-move approach [42] proposed two methods to overcome the drawback of [15]. Researcher [43] proposed a nonlinear internal model control for stiction compensation. But, this model required the physical forces acting on the control valve.

An on-line method is proposed in [44] for stiction compensation. A fuzzy logic observer is used to compensate friction in servomechanisms in [45] and [46]. Neural networks are used in [47] for friction compensation. Authors [48] proposed optimization method for stiction compensation. This optimization method can lead to better results than the other methods. However, tuning the parameters is a difficult task and this method is computationally expensive to be applied in sticky valves. A non-model based method of stiction compensation for control valves has been presented in [49]. The method is based on the Knocker approach with addition of a level of supervision to analyze process error and to interact with a PID controller. This method requires only an estimate of stiction for the Knocker pulses and an estimate of the error derivative achievable using Knocker; both parameters are easily obtained with online measurements. Very useful approaches to compensate static friction [50] in control valves were presented. The objective of this method is to remove/ reduce stiction-induced oscillations by changing controller tuning.

VI. CLOSED LOOP RESPONSE WITHOUT STICTION COMPENSATION

The data-driven two-parameter stiction model proposed by [13] is considered for this work. The model consists of two parameters namely the size of dead-band plus stick-band S (specified in the input axis) and slip jump J (specified on the output axis) as shown in Figure 3. Using two-parameter stiction model, which predicts the behavior of a sticky valve more precisely, does not need extensive prior information about the process and the controller, and can track set point changes during operation. For assessment of closed-loop behaviour, the control valve output drives a first-order plus dead time process $G_p(s)$ and receives its OP reference input from a PI controller $G_c(s)$ represented in equation (2).

$$G_p(s) = \frac{3e^{-10s}}{10s+1} \quad ; \quad G_c(s) = 0.2\left(\frac{10s+1}{10s}\right) \qquad (2)$$

The simulated application performance of closed loop control system without stiction compensation as shown in Fig. 6 (a)-(d) it shows the limit cycles induced in this control loop by the valve, together with the plots of valve position MV versus valve demand OP. The limit cycles are observed even though the set point to the loop was zero [13]. That means, they were internally generated and sustained by the loop in the absence of any external set-point excitation. The stiction were selected as 5% and jump were selected as 4% for this simulation work. The sampling time has been chosen as 1sec.

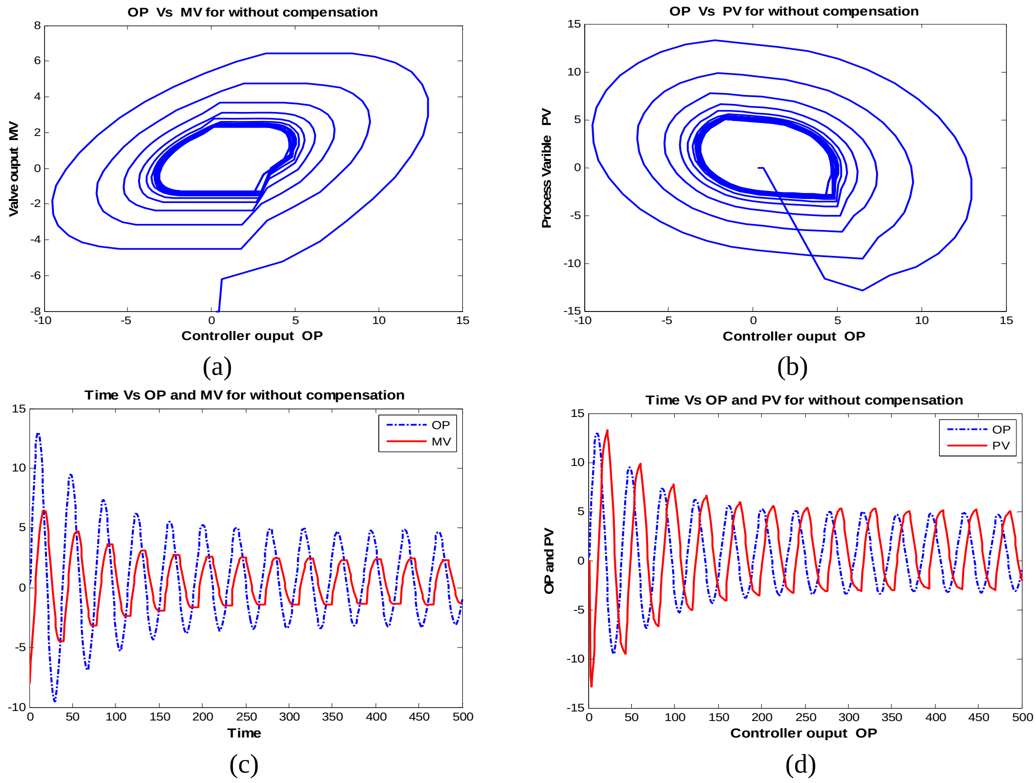
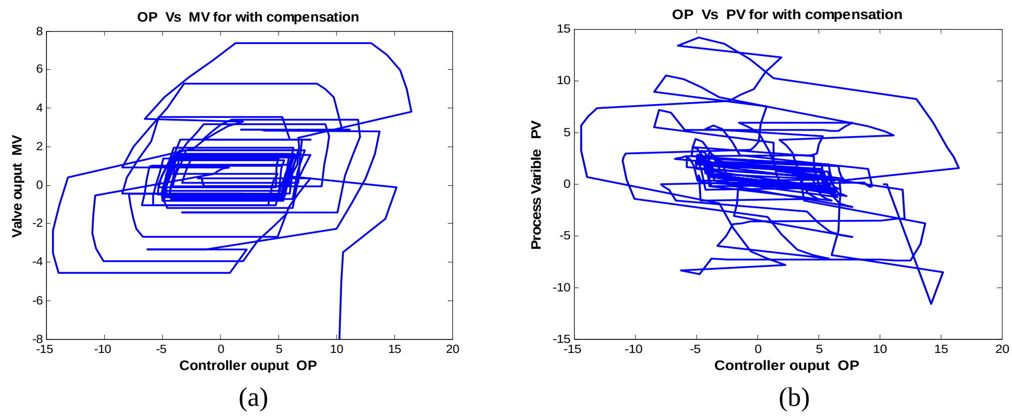
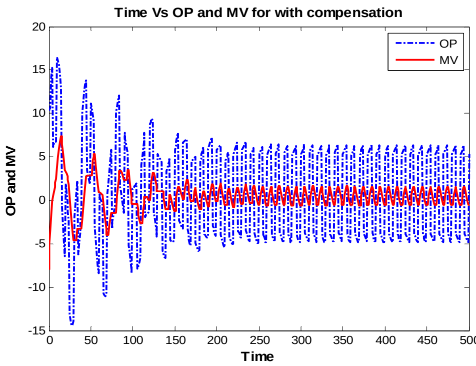


Figure 6. Performance of the closed loop system without stiction compensation (a) Response of OP Vs MV(b) Response of OP Vs PV (c) Response of Time Vs OP and MV (d) Time Vs OP and PV

VII. STICTION COMPENSATOR WITH KNOCKER METHOD

The block diagram of stiction compensation using pulse signal (knocker method) is shown in Figure 4. The two-parameter data driven model proposed by [13] is used to simulate the behavior of sticky valve. In this section the performance of the proposed method using pulse signal for stiction compensation for various parameters as showed Figure 7 (a)-(g). Figure 7 (e) to (g) represent the performance of controller outputs, valve outputs and process variables for proposed and without stiction compensation respectively. The performance analyses / results of these parameters are given in Table 1.It is noticed that the magnitude value of controller output for stiction with compensation is of higher value than the stiction without compensation [Figure7 (e)]. However, Figure 7 (f) shows the magnitude of the valve output with compensation which is of lower value than the magnitude of the valve output without compensation. Finally, the process variable for stiction with compensation shows better response compared stiction without compensation, which is shown in Figure 7(g). The performance analyses/ results of these parameters are given in Table 1.





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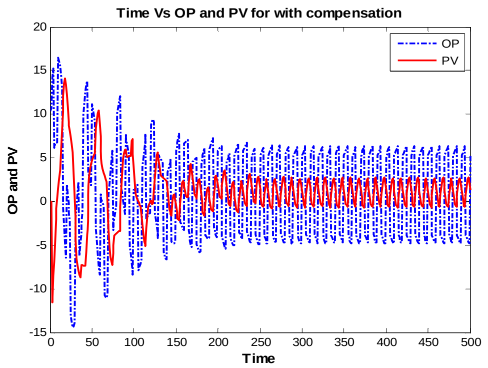

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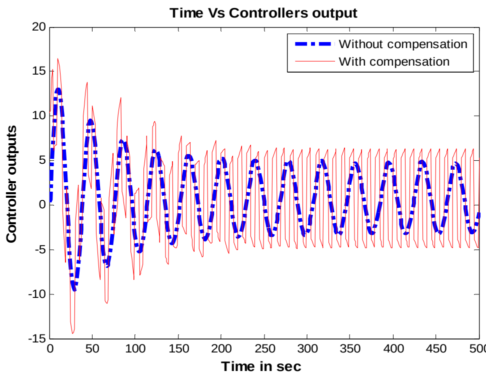

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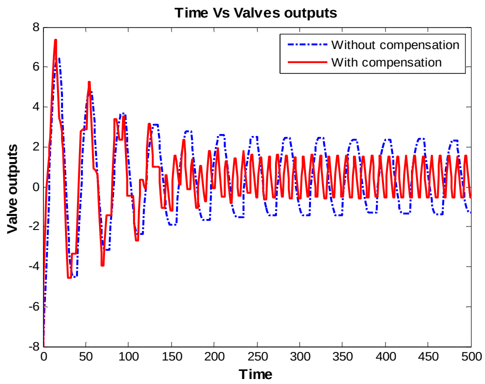

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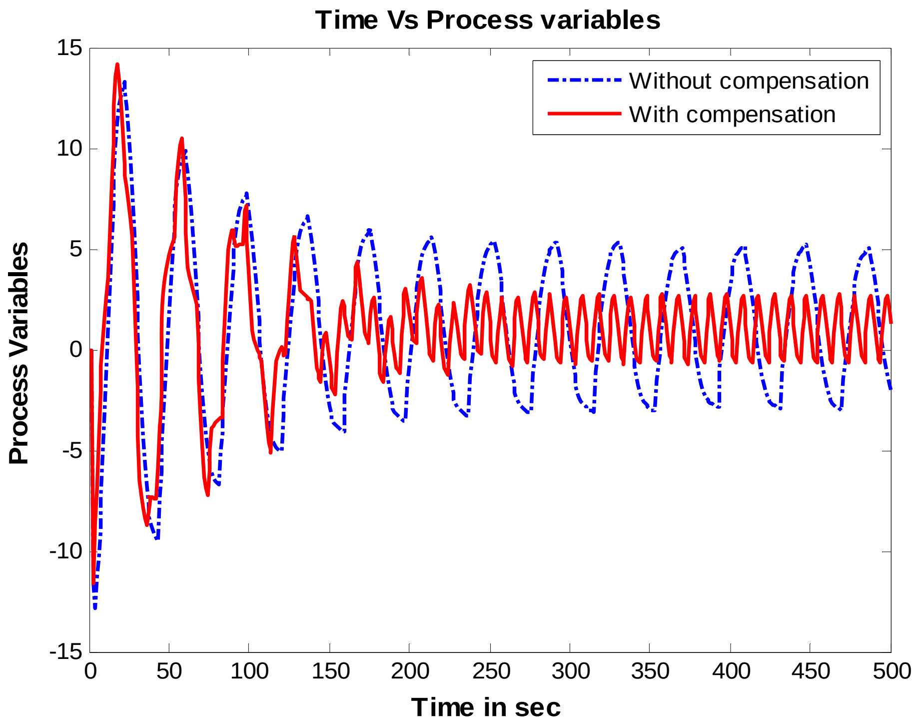


(g)

Figure 7. Performance of the closed loop system with stiction compensation using pulse signal

VIII. PROPOSED COMPENSATION METHOD

Earlier research works show that knocker method keeps the valve stem in the same position for a longer period than the constant reinforcement method. The performance of reducing control valve stiction using constant reinforcement method is clearly worse than those obtained using knocker method. The reduction of stiction nonlinearity is achieved only at the cost of an aggressive stem movement. But, such an aggressive stem movement may damage the control valve and it may lead the process variable still worsen than the previous performance. Considering the above drawbacks in various existing compensation methods, a new method has been proposed in this paper. The sinusoidal signals have been considered for stiction compensating purpose instead of pulse signal. In this proposed method a minimum-oscillatory output without forcing the valve stem to move faster is achieved which is wider than the normal and is claimed as the most important characteristic of the presently proposed method.

The proposed valve stiction compensating method using sinusoidal signal is shown in Figure 8. The knocker method uses the square wave which contains harmonics and causes sudden changes in the manipulated variable may affect the control valves subsequently. In this proposed method the sinusoidal wave is considered since it contains only the fundamental frequency and it gives better performance by reducing the magnitude of stiction. The output of uncompensated wave is shown in Figure 6(d). The magnitude and frequency of oscillation of uncompensated system output are noted down from this Figure Then the compensating sinusoidal signal amplitude and frequency are calculated as shown below. Let

'a' be the amplitude of uncompensated stiction output =5; and
'T' be the period of oscillation of uncompensated stiction output=40 sec.

Then the compensating sinusoidal signal can be represented as in equation (3)

$$f_k = A \sin \omega t \qquad (3)$$

Where; A=Amplitude =2*a=10; and ω=2πf; $f = \frac{1}{T}$;

In this compensating method the ω value have been selected as $\omega = 8 * \frac{2\pi}{T} = 0.1571$ rad/sec.

The sinusoidal signal is used in the closed loop system for compensating the stiction nonlinearity. This reduces the amplitude of the process variable which is shown in Figure 9(g).

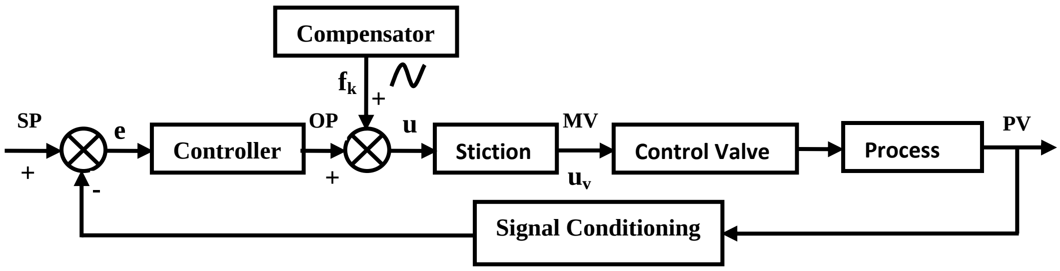
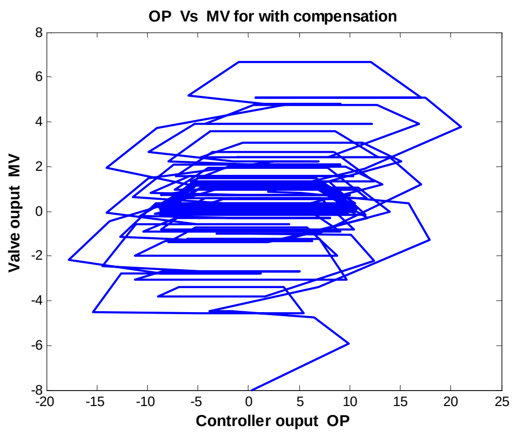
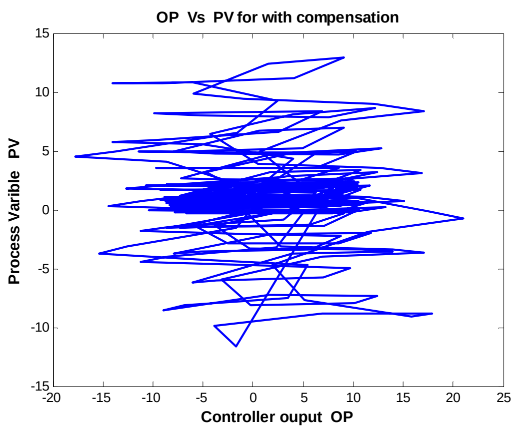


Figure 8. closed loop control system with stiction compensator using sinusoidal signal

The two-parameter data driven model proposed by [13] is used to simulate the behavior of sticky valve. In this section the performance of the proposed method using sinusoidal signal for stiction compensation for various parameters as showed Figure 9 (a)-(g). Figure 9 (e) to (g) represent the performance of controller outputs, valve outputs and process variables for proposed and without stiction compensation respectively. The performance analyses / results of these parameters are given in Table 1.



(a)



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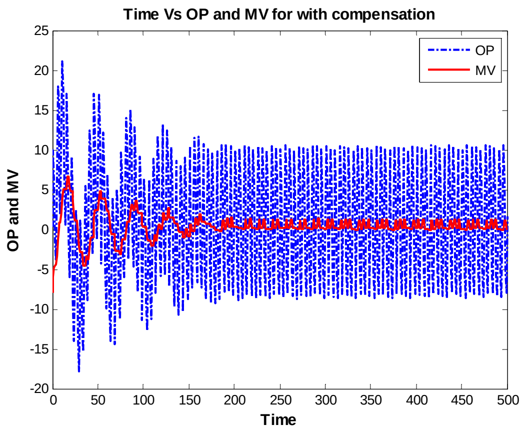

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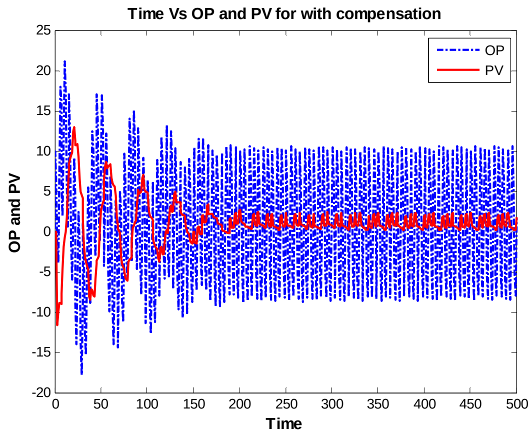

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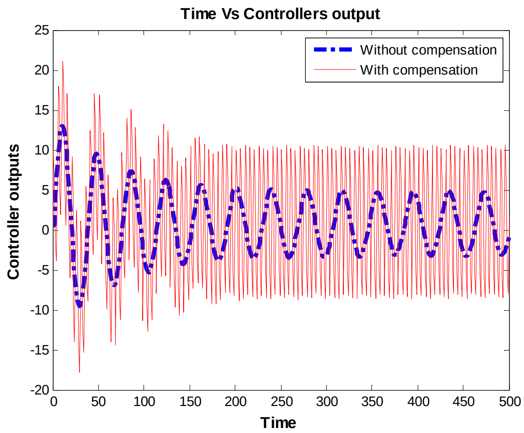

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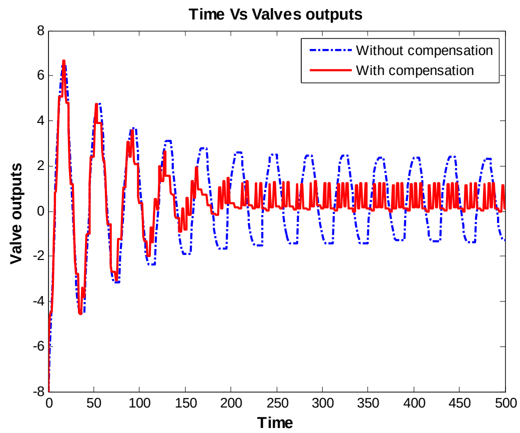

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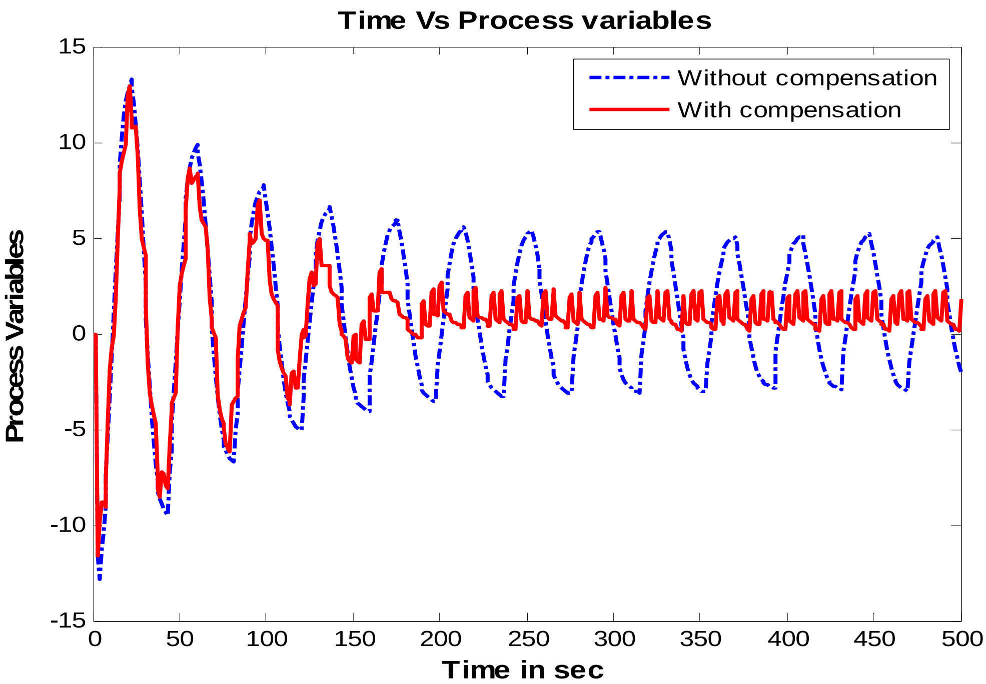

(g)

Figure 9. Performance of the closed loop system with stiction compensation using sinusoidal signal

IX. RESULTS AND DISCUSSIONS

Figure 7 and Figure 9 show various responses with and without stiction compensation for the application of pulse signal and the sinusoidal signal respectively. From the graph it is observed that the stiction compensation started at t=186sec. It is also noticed that the magnitude of the process variable with stiction compensation using proposed method is 2.2755, whereas using the pulse signal PV obtained (reported) is 3.344 which is depicted in Table 1. Hence, it is concluded that the proposed method yields better response than available other method especially knocker method of stiction compensation. It is also observed that the IAE and ISE values are reduced significantly in proposed stiction compensation technique whereas these values are increased using pulse signal as stiction compensation purpose which is shown in Table I.

TABLE I. PERFORMANCE ANALYSIS OF THE PROPOSED METHOD

Conditions	Performance Analysis				
	OP	MV	PV	ISE	IAE
Without Compensation	8.477	3.88	8.546	130.2	11.41
Compensation By Knocker method	11.34	2.17	3.344	946.5	30.76
Compensation By proposed method	19.45	1.2752	2.2755	56.98	7.548

X. CONCLUSION

In this work, a simple model-based method for compensation of stiction for control valves has been suggested. Simulation studies have shown that the proposed method has better performance for different levels of stiction when compared with Knocker method. The magnitude performance of the proposed method is better than the existing stiction compensation techniques. In order to check the effectiveness of the proposed compensator the magnitude of stiction is decreased from 3.344% to 2.2755% using knocker method and the responses are given in Figure 7 and Figure 9. The results clearly show that the proposed approach provides an improved and smoother valve operation, compared to the knocker method. The results also show that the IAE and ISE values are reduced significantly using the proposed method than the knocker method. Hence, the proposed method can be implemented in control loops of different industrial processes.

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