Modelling and Dynamic Analysis of Pneumatic Control Valve with Stiction

S.Sivagamasundari[1] *D.Sivakumar*[2]

Abstract

High performance of control loops is necessary to ensure high product quality and low cost in chemical plants. Often poor performance can be detected by the operator, but many times the problem may propagate to other loops, making it difficult to detect the root cause. One of the many reasons for degrading performance is stiction found in control valves. It hinders the proper movement of valve stem and consequently affects the control loop performance. It is therefore important for control engineers to understand stiction phenomena and to know how to deal with them. This paper focuses on the development of a model for control valve stiction, through simulation, which can be used for the dynamical analysis of valve stiction effects on process control loop performance. The model developed here use simple empirical relationships between controller output and the valve position to describe valve stiction with just a few parameters that can be determined from operating data. The proposed stiction model captures the stiction behaviour and can be used to investigate by analysis and simulation, the properties of stiction that are relevant to control design.

[1]Department of Instrumentation Engg., Annamalai University, Annamalainagar, India. Email : sivagamasundari67@gmail.com

[2]Department of Instrumentation Engg., Annamalai University, Annamalainagar, India. Email : dsk2k5@gmail.com

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1. Introduction

The field of controller performance monitoring has received much attention in the engineering research literature. However the diagnosis of poor performance remains an open area. The reason for poor control loop performance may be due to poor controller tuning, presence of disturbances, process and / or actuator non linearities. Non linearities degrade the performance of the controller in several ways. They may produce oscillations in process variable, shorten the life of control valve, may upset process stability and in most cases lead to inferior quality end products, thus causing larger reduction rates and reduced profitability.

The non-linearities may be present in the process itself or in the actuators or control valves. The most popular problem is the incorrect tuning of controllers which may be due to non-linearities present in the process itself, can be faced by process identification and auto tuning. Instead, a more common cause should be sought in the presence of static friction in actuators, which causes a delayed and sluggish actuation of changes in manipulated variables, required by the control system. Stiction found in pneumatic control valves is one of the greatest obstacles in high precision process control systems. It can cause steady state and tracking errors, while it may result in limit cycles. Therefore its influence on the response of systems must be seriously considered.

Control strategies that attempt to compensate for effects of stiction inherently requires a suitable model to predict and to compensate for the stiction. A good stiction model is also necessary to analyse stability, predict limit cycles, find controller gains and perform simulations. Both detailed physical models and purely empirical models have been used to simulate valve stiction. Physical models [1] describe the stiction phenomenon using force balance based on Newton's second law of motion. The main disadvantage of these models is that they require knowledge of several parameters such as the mass of moving parts and different types of friction forces that cannot be easily measured and are dependent on the type of fluid and valve wear. On the other hand empirical or data driven models [2] use simple empirical relationships between controller output and the valve position to describe valve stiction, with just a few parameters that can be determined from operating data. Srinivasan et al.[3] uses a Hammerstein model identification approach along with one parameter stiction model [4] to detect and quantify stiction. The one parameter model does not catch the true stiction behaviour. Choudhury et al.[1,2] have discussed the definition of stiction thoroughly, distinguished it from other valve nonlinearities, and proposed a new two parameter data driven model of stiction. The model derived by Choudhury [2] has been widely used in the study of valve stiction. In this work the complexity of Choudhury's model is reduced and another data driven model is proposed with straight forward logic flow.

The paper is organized as follows. Section 2 recalls the basic structure of a control valve system. Stiction behaviour is explained in section 3. The physical model of stiction is given in section 4. In section 5, the new data driven valve stiction model is proposed. Based on this model the effects of control valve stiction on a control loop are illustrated. The application of the proposed model to simulated example is presented in section 6. Section 7 analyses the effects of stiction under closed loop condition. Conclusion is given in section 8.

2. The Structure of a Control Valve

The general structure of a pneumatic control valve is shown in fig.1. The valve is closed by elastic force and opened by air pressure. Flow rate is changed according to the plug position which is determined by the balance between elastic force and air pressure.

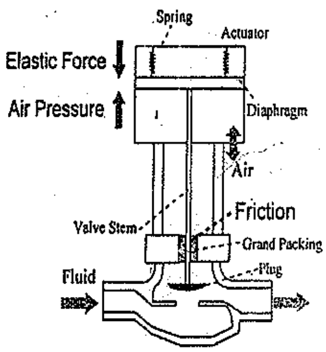


Figure 1 : Pneumatic Control

The plug is connected to the valve stem. The stem is moved against static or kinetic frictional force caused by packing, which is a sealing device to prevent leakage of process fluid. Smooth movement of the stem is restricted by excessive static friction. The valve position cannot be changed until the controller output overcomes static friction, and it is suddenly and considerably changed when the difference between elastic force and air pressure exceeds the maximum static frictional force.

3. Stiction Behaviour

Stiction (also known as stick-slip or static friction) in control valves is thought to occur due to seal degradation, lubricant depletion, inclusion of foreign matter, activation of metal sliding surfaces at high temperatures and tight packing around the stem. The resistance offered from the stem packing is often cited as the main cause of stiction. One other very common cause of stiction is indirectly due to regulations on Volatile Organic Compound (VOC) emissions. In many plants, a team monitors each valve for VOC emissions, usually between the packing and the stem. If any minute leakage is detected, packing in the valve body is tightened, but tightened far more than is necessary. This causes the valve to stick, making the process run less efficiently with increased energy consumption. Stiction often varies over time and operating regimes. Since wear is also non-uniform along the body, frictional forces are different at different stem positions, when the control loop is at steady state, and if a valve exhibits this behaviour, persistent oscillations in process variable on either side of the set point are observed.

Understanding the type of oscillations caused by a sticking valve in a control loop requires a good grasp of the stick slip phenomenon. Stiction in control valves leave a distinct qualitative shape in the controller output and process variable. These shapes can be generally categorized as being square, triangular or saw toothed and depends primarily on the type of controller structure implemented. Under some condition, a control valve will exhibit stick-slip behaviour as shown in fig. 2.

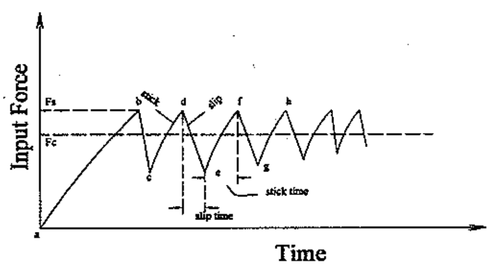


Figure 2 : Force Profile during Stiction

The input force (control action) observed during motion is sketched. During the stick, (interval a-b) the force rises. At point 'b', the force reaches F_s, the level of static friction when the system has been at rest for considerable time, and slip begins. During interval b-c slip occurs. At point 'c', the pin is arrested and the spring force again begins to rise entering a stable limit cycle c-d-e. Here F_s is the static friction and F_c is the coulomb friction.

4. Physical Model of Valve Stiction

For a pneumatic sliding stem valve, the force balance equation based on Newton's second law can be written as.

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

Where,

M = Mass of the moving parts;

x = Relative stem position;

$F_e = S_a u$

= Force applied by pneumatic actuator

S_a = Area of the diaphragm,

u = Valve input signal (controller output))

F_r = -Kx = spring force (K = Spring constant)

$F_p = -\alpha\Delta p$ = force due to fluid pressure drop

α = plug unbalance area,

Δp = fluid pressure drop across the valve

F_i= Extra force required to force the valve to be into the seat

F = Frictional force.

Here F_i and F_p assume to be zero because of their negligible contribution in the model. Now the force balance equation can be written as

$$\dot{x}_1 = x_2 \qquad (2)$$

$$M\dot{x}_2 = S_a u - kx_1 - F \qquad (3)$$

Where, x_1= Position of the stem;

$x_2 = v =$ Stem velocity (4)

F= the frictional force and is given by,

$$F = \begin{cases} F(v) & \text{if } v \neq 0 \\ F_e & \text{if } v = 0 \ \& \ |F_e| < F_s \\ F_s \operatorname{sgn}(F_e) & \text{if } v = 0 \ \& \ |F_e| \geq F_s \end{cases} \quad (5)$$

Where,

$$F(v) = F_c[\operatorname{sgn}(v)] + (F_c - F_s)e^{(v/v_s)}[\operatorname{sgn}(v)] \quad (6)$$

The equations (1-6) describe the valve model with friction forces.

Here, F_v = Viscous friction coefficient,

F_s = Static friction,

F_c = Coulomb friction,

v_s = Stribeck's constant.

The function 'F' is easily obtained by measuring the friction force for motions with constant velocity.

A disadvantage of a physical model of a control valve is that it requires several parameters to be known. The mass, 'm', spring constant 'K' and typical friction forces depend upon the design of the valve.

5. The Data Driven Model Formulation

Fig.3 shows the typical input output behaviour of a sticky valve. Without stiction the valve will behave like a linear

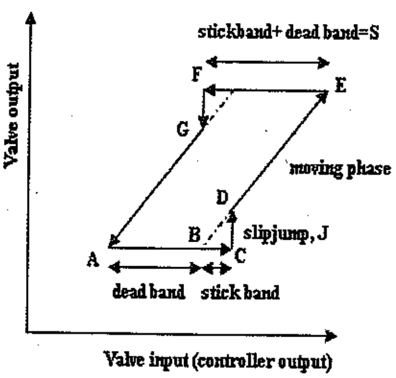


Figure 3 : Typical Stiction Behaviour

system. (any amount of valve input would result in the same amount of valve output). After the controller output overcomes the dead band (AB) and stick band (BC) of the valve, the valve jumps to a new position (D) and continues to move (DE). Due to very low or zero velocity, the valve may stick again in between points E and F while travelling in the same direction. In such a case, the magnitude of dead band is zero and only stick band(S) is present. This can be overcome if the controller output signal is larger than stick band only. The dead band and the stick band represent the behaviour of the valve when it is not moving, though the input to the valve keeps changing. Slip jump (J) represents the abrupt release of potential energy stored in the actuator chamber due to high static friction. The magnitude of slip jump is very crucial in determining the limit cyclic behavior introduced by stiction.

However for a sticky valve static and dynamic frictions must be taken into account. The dynamic friction band f_d is given by (S-J)/2 and static friction band f_s is given by (S+J)/2; where J is the slip jump and S is the sum of stick band and dead band. The slip jump is equal to stick band. Based on the sticky valve behaviour a new valve stiction model is proposed. The valve sticks only when it is at rest or it is changing its direction it comes to a rest momentarily. Once the valve overcomes stiction, it starts moving and may keep on moving for sometime depending on how much stiction is presenting the valve. In this moving phase, it suffers only dynamic friction which may be smaller than the static friction. it continues to do so until its velocity is again very close to zero or it changes direction.

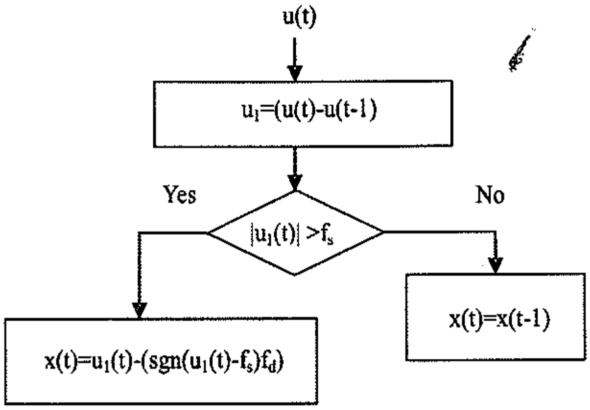


Figure 4 : Flow Chart Of The Proposed Valve Stiction Model

Figure 4 shows the flow chart of the proposed valve stiction model. Here u(t) is the controller output,

f_s = static friction= (S+J)/2

f_d=dynamic friction=(S-J)/2

x(t) is the valve position.

6. Valve Simulation

The purpose of simulation is to determine the influence of the friction terms in the model. The non linearity in the model is able to induce limit cycles in the feedback control loop. The valve model is driven by a periodic ramp signal in open loop. During closed loop condition, input to the valve is given from controller, so controller output is acting as input to the valve stiction model and valve position is the output of the model.

A. Case(i) : Linear

Using the aforesaid model, the response of the control valve to a periodic ramp signal in the absence of stiction (f_s=f_d=0.0001(closer to zero)) is obtained and is shown in fig.5. This can be assumed as a linear valve in the absence stiction. The step response of the valve in the absence of stiction is shown in Fig.6. The response is similar to that of a first order system with no offset.

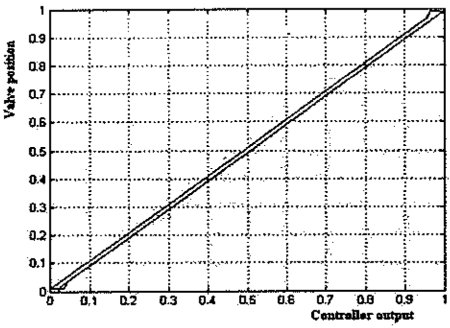


Figure 5 : Valve Behaviour In The Absence Of Stiction

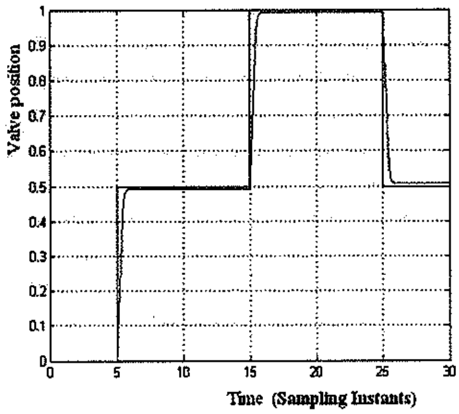


Figure 6 : Step Response Of The Valve In The Absence Of Stiction

B. Case(ii): Pure Dead band

When the stick band is zero, there is no slip jump and J=0; in this condition f_s = f_d, but it is a non zero value. In this condition only dead band arises because on changing the direction, the valve remains stationary until the net applied force is large enough to overcome the static friction. If the static friction is larger dead band will also be larger. This condition is shown in Fig.7. The step response for this condition will be similar to case (i) and is presented in Fig.9.

C. Case(iii): Stiction and Dead band

When f_s > f_d the valve with high initial static friction exhibits a jumpy behaviour that is different from dead band.

When the valve starts to move, the friction force reduces abruptly from f_s to f_d, the initial velocity is faster making f_s equal to f_d leading to jumpy behaviour as shown in fig.8. The corresponding step response is given in Fig.9.

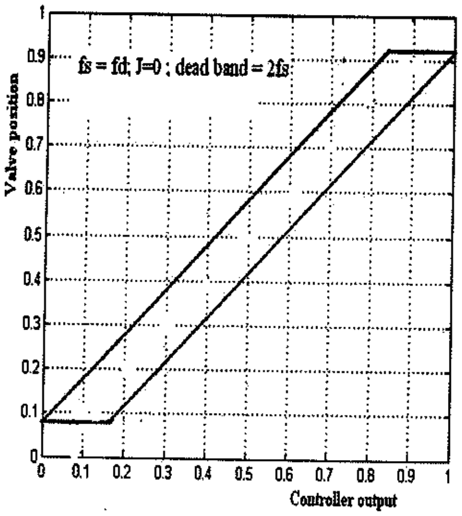
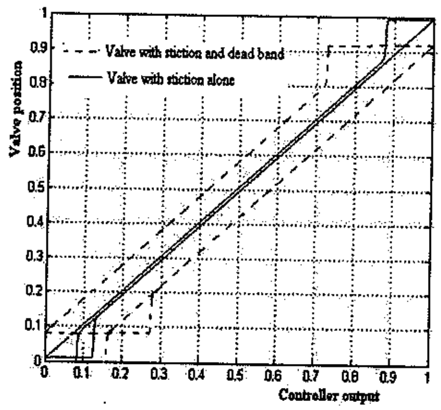


Figure 7 : Valve with Dead Band



Fiigure 8 : Value with Stiction and Dead Band

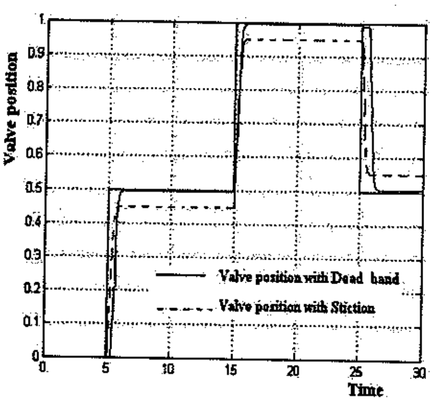


Figure 9 : Step Response of a Valve under Stiction and Dead Band

D. Case(iv):High Stiction

Under high stiction, the actuator piston applies increasing pressure in the air cylinder causes a temporary valve stem stopping and leads to a jumpy movement as shown in fig.10.

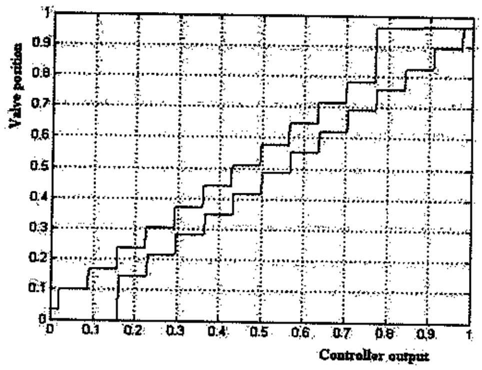


Figure 10 : Jumpy Valve Movement due to Stiction

The valve response under this condition for a periodic ramp signal is shown in Fig.11. Under such high level of stiction, the stiction compensators will not give satisfactory results and the control valve has to be replaced.

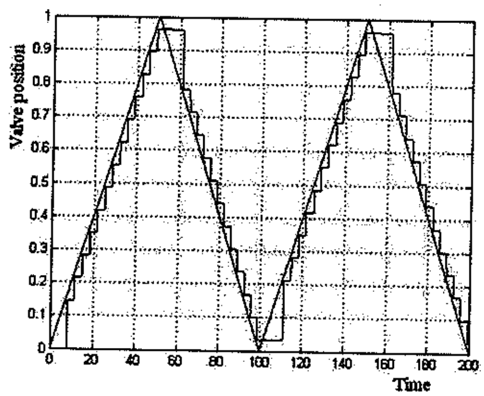


Figure 11 : Valve Response in the Presence of Stiction for Periodic Ramp Signal

Since the model is directly based on the dynamics of the valve, it is very simple to use for the purpose of simulation and can quantify stiction as a span of input signal. Also the parameters used in this model are easy to understand, realize and relate to real stiction behaviour. Though this is an empirical model, it is observed that this model can correctly reproduce the behaviour of stiction model based on physical principles.

7. Effects of Valve Stiction under Closed Loop Condition

For assessment of closed loop behaviour, the valve output drives a first order plus dead time process $G_p(s)$ and receives its reference input from a PI controller $G_c(s)$ where,

$$G_P(s) = \frac{1.5e^{-1.07s}}{5.93s+1}; G_C(s) = 1.1 + \frac{1.1}{2.5s}$$

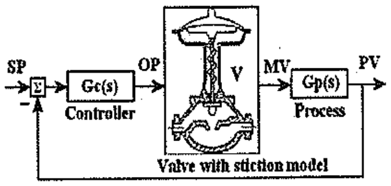


Figure 12 : Closed Loop System with Valve Stiction Model

Fig .12 shows the block diagram of a control loop in the presence of stiction. Valve dynamics are observed only after the starting of stem movement; stiction phenomenon if present will precede the valve dynamics. It is assumed that the valve is suffering from strong stiction. The triangular shape of the time trend of process output shown in Fig.13 is one of the characteristics of stiction [6] and this looks similar to Fig.2 The presence of stiction causes limit cycles of the process output. Fig.14 shows the mapping of controller output vs. valve position and it clearly shows the stiction phenomena in the valve. It is common practice to use the mapping of controller output vs. process output for valve diagnosis which is shown in Fig.15. However in this case such a mapping only shows elliptical loops with sharp turn around points. The reason is that, this map captures not only the valve characteristics but also the dynamics of the process $G_p(s)$, which in this case is a first order lag plus dead time.

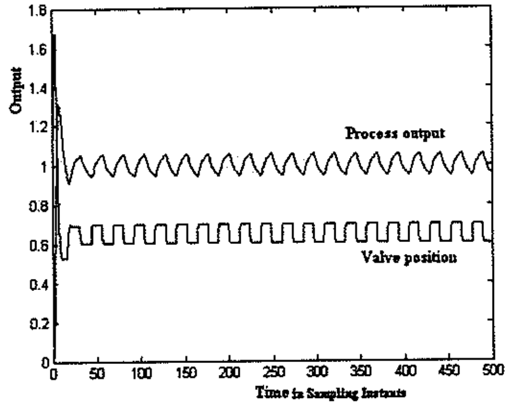


Figure 13 : Closed Loop Response In The Presence Of Stiction

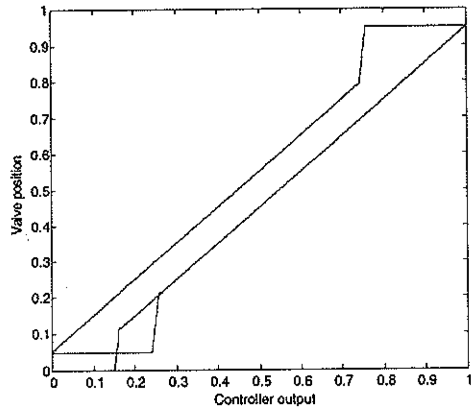


Figure 14 : Controller Output Vs Valve Output

This behaviour, results in oscillatory control signal and process output. The corresponding simulation results are shown in fig. 13. The above simulation results show that a high value of stiction leads to a high magnitude and high frequency oscillations. This result clearly exhibits the typical rectangular waveforms of the oscillations of the valve output and the triangular wave forms of the process output, which is the effect of stiction. The period of oscillation depends on the process dynamics, controller dynamics and valve characteristics. The response between controller output and valve position is shown in Fig.14. Here the value of slip jump(J) is much larger. In practical situation this response is difficult to obtain, since the valve position cannot be measured directly. Usually the response between controller output and process output is obtained and is shown in Fig.15.

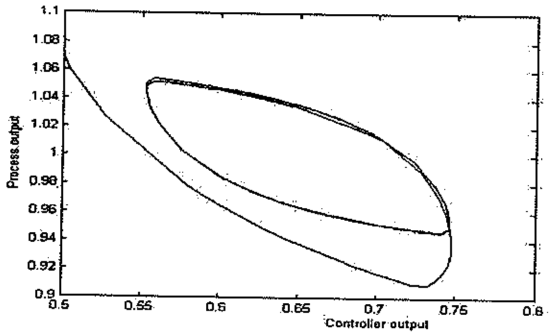
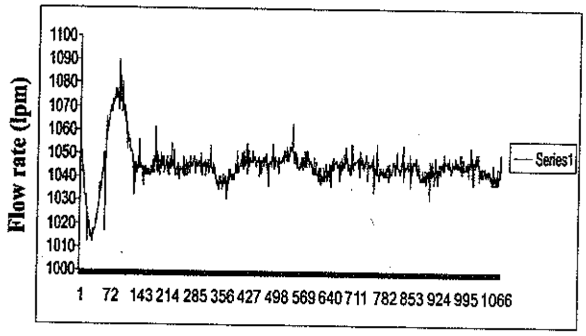


Figure 15 : Controller Output Vs Process Output

8. Practical Examples Of Valve Stiction

The effects of stiction from the investigation of data acquired by conducting an experiment on the laboratory flow control loop are explained in this section. The flow loop is a slave loop, cascaded with a master temperature control loop. In total 1100 samples are collected at a sampling rate of 0.01sec. Fig.16 shows the step response of flow process showing stiction phenomena. Fig.17 shows the controller output Vs process output plot of laboratory flow loop which is similar to that of the simulated response shown in Fig.15 and that the model is validated.



Time in Samples

Figure 16 : Step Response of Flow Process Showing Stiction Phenomena

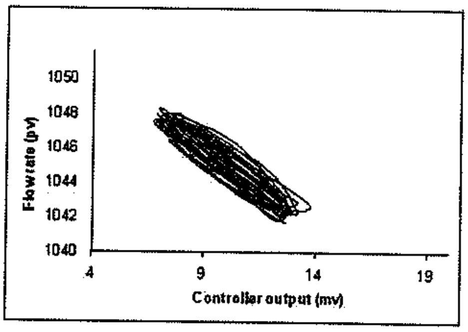


Figure 17 : Controller Output Vs Process Output Of Laboratory Flow Process

9. Conclusion

In this work, a structurally simple and logically straightforward approach for modelling a valve stiction is proposed. The model has parameters that can be directly related to plant data and it produces the same behaviour as the physical model. The model needs only the specification of static and dynamic friction values. It overcomes the disadvantages of physical modelling of a control valve, which require the knowledge of the mass of the moving parts of the actuator, spring constant and the friction forces. The effect of the change of these parameters cannot easily be determined analytically. The proposed model overcomes some of the disadvantage of the existing models and this control valve stiction model can be used to study the stiction phenomena and its effects on closed loop control performance. Both closed loop and open loop results have been presented and validated to show the capability of the model. This data driven model is capable of handling stochastic inputs and can be used to perform simulation of stiction in Matlab's Simulink environment in the studies of stiction related control loop problems.

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Author's Biography

Mrs. S.Sivagamasundari, currently working as a Reader in the Department of Electronics & Instrumentation Engineering, Annamalai University, India has a teaching experience of more than 17 years. She obtained her B.E. (Electronic and Instrumentaton) degree and went on to complete her M.E. (Process control and Instrumentation), both from Annamalai University. Her research interests include Nonlinear Process Control and Instrumentation, Adaptive control and System identification. The author has also presented her research findings as papers in National and International conferences.

Dr.D.Sivakumar, a Professor in the Department of Electronics & Instrumentation Engineering, Annamalai University, India has a teaching experience of more than 25 years. He obtained both B.E. (Electronics & Instrumentation) and M.E. (Power Systems) degrees from Annamalai University. Further, he completed his Ph.D. Research programme at PSG College of Technology, Bharathiar University, Coimbatore. His research interests include Control System, Process Control, Fault Tolerant Control, Signal & Image Processing, Adaptive control and System identification. He has successfully guided two PhD scholars. He has to his credit research papers presented in many National and International conferences and published in National as well as International Journals. He is a life member in professional bodies like ISTE and System Society of India.