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Issues in Modeling Stiction in Process Control Valves

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***Abstract*— Stiction has been reported as the most commonly occurring nonlinearity in control valves. In the literature, mechanistic and data based models have been proposed to characterize stiction. In this paper, the available models are critically analyzed. The complexities associated with modeling stiction are highlighted. It is shown through experiments on industrial valves that in the presence of static and dynamic friction, the valve behavior is dependent on the rate of the valve input. An approach to model this rate dependent valve behavior - which is not considered in existing data driven models - is proposed.**

I. Introduction

Process control valves which act as a final control element in a control loop not only affect the performance of higher level control hierarchy, but also the overall profitability of the process. A good discussion on valve nonlinearities can be found in Choudhury *et al.* [1]. When valve nonlinearities exceed nominal values, stable or unstable limit cycles develop in a control loop. It has been reported that static friction in control valves is a major source for limit cycles in control loops.

The development of a physical model for a valve in the presence of stiction requires knowledge about the stem mass, spring constant, static, dynamic and viscous friction coefficients. In contrast, data driven models are advantageous in that they are built using normal operating data and sufficiently mimic the physical model without the need for several parameters. Stenman *et al.* [2] used a simple one parameter data driven model for characterizing stiction. Choudhury *et al.* [1] proposed a two parameter data driven model for stiction and validated the model with industrial data. This was followed up by a similar data based model by Kano *et al.* [3]. The obvious importance of this problem necessitates a careful and thorough understanding of the stiction phenomenon and the models (either mechanistic or data based) for characterizing the stiction phenomenon. It is also important to model and understand stiction behavior that ultimately has an effect on the overall closed loop behavior. In that sense, it is important that a distinction be made between models that are comprehensive from a completely fundamental viewpoint for stiction (either in open loop or closed loop and for all types of input signals) and models that are sufficient from a closed loop perspective.

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A. Contribution of this work

This paper addresses various issues in modeling stiction. While there are a number of models for stiction, validation studies with real stem position data are minimal. Even models that have been validated are usually based on the final flow measurement but not the valve stem measurement. Further, in industry, the data is obtained by stoking the valve with a series of steps to identify valve characteristics. It is not easy to find data in the literature for the response of a valve when stoked with a ramp input, which provides exemplifying information vis a vis the various stiction mechanisms. It is shown through experiments on industrial valves that in the presence of static and dynamic friction, the valve behavior is dependent on the rate of the valve input.The impact of this rate dependent behavior on various stiction related activities such as limit cycle analysis, diagnosis and compensation are also discussed.

II. Mechanistic Valve behavior - Simulation study

A control valve has at least two components:

- a valve body that houses a valve seat through which the fluid flows and
- an actuator that responds to the applied signal and causes the motion of valve seat through a stem resulting in modifications to the fluid flow.

Additionally, a valve may contain a positioner that moves the stem to its desired position. Figure 1a shows a schematic of a spring and diaphragm actuator operated valve. The positioning of the stem is achieved by a balance of forces acting on the stem: forces due

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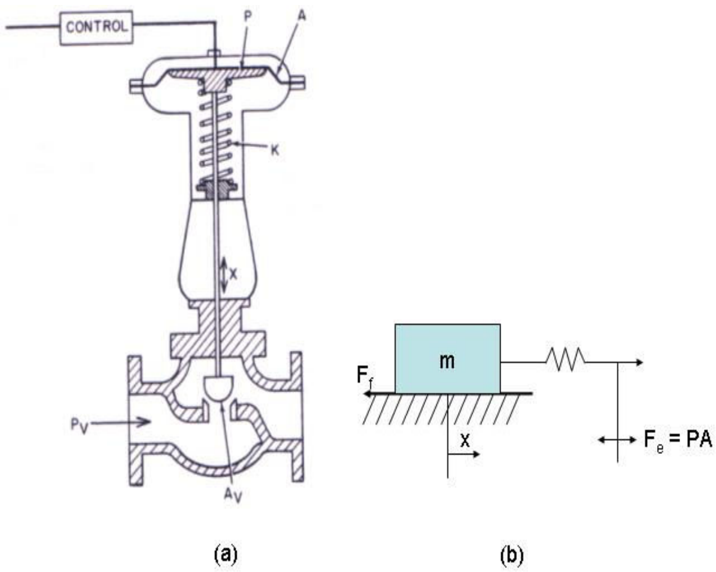

Fig. 1. (a) Control Valve Schematic (Air to Close) (b) Spring-Mass equivalent of Valve's moving part

to pressure on the diaphragm, the spring travel, and the fluid forces on the valve plug. In this study, we restrict ourselves to the study of stiction phenomenon in pneumatically operated spring and diaphragm actuators. More details on the working of an actuator can be found in [4]. The valve behavior is simulated using equations 1, 2 and 3.

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + Kx = PA - P_vA_v - F_f \quad (1)$$

$$F_f = \begin{cases} F(v) & if \;\; v \neq 0 \\ F_e & if \;\; v = 0 \;\; \& \;\; |F_e| < F_s \\ F_s\, sign(F_e) & if \;\; v = 0 \;\; \& \;\; |F_e| \geq F_s \end{cases} \quad (2)$$

$$\text{where } F_e = P * A \;\; \& \;\; v = \frac{dx}{dt} \;\; and$$

$$F(v) = F_c sign(v) + (F_s - F_c)e^{(v/v_s)^2} sign(v) \quad (3)$$

Here A is the effective diaphragm area, A_v is effective inner valve area, K is the spring rate and P is the applied pressure on diaphragm, P_v is the pressure drop across the valve, m is the mass of stem, b is viscous friction, F_f, the friction force and x is the stem travel. F_c represents the dynamic friction force that opposes the sliding motion of the stem, F_s represents the static friction force that the stem has to overcome to move from rest. The last term in equation 3 denotes the Stribeck friction force, which decreases as stem movement occurs. For simplicity, the fluid force on the valve plug (P_vA_v) is neglected in all our simulations. Table I summarizes the parameters that are used in the simulations. These values are representative of typical industrial control valves [4]. The open loop behavior of the valve is obtained by sufficiently ramping the actuator supply air-pressure to achieve full stem travel.

TABLE I
VALVE PARAMETERS AS SEEN IN PRACTICE[4]

Parameter	Description	Value
P	Applied Actuator Pressure	psi
A	Effective Diaphragm Surface area	100 in^2
m	Mass of Stem and Plug	3 lb
K	Spring rate	300 lbf/in
b	Viscous coefficient	3.5 lb/s
F_c	Coulomb friction	320 lbf
F_s	Static friction	384 lbf
v_s	Stribeck constant	0.01 in/s

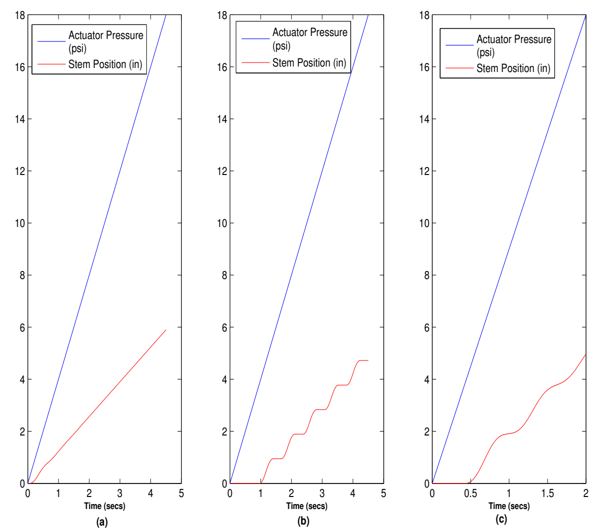

Fig. 2. Valve behavior (a) in the absence of static and dynamic friction forces, (b) in the presence of friction forces for an input slope of 4 and (c) in the presence of friction forces for an input slope of 9.

Figure 2 shows the stem position for three different cases. The actuator air pressure was ramped from 0 to 18 psi. The input pressure was ramped at two different slopes, 4 and 9 respectively. Figure 2a shows the stem measurement when frictional forces are absent and Figures 2b and 2c show the valve behavior in the presence of static and dynamic friction forces. Both Figures 2a and 2b are obtained with an input pressure ramp with a slope of 4. Ramping the input rate at a higher slope (=9) results in a different behavior. This is shown in Figure 2c. For an input pressure (P) applied with a slope of 4, the stem switches between periods of stick and slip (see Figure 2b), resulting in a *staircase pattern* in the stem position. However when the input pressure (P) was ramped at a higher rate (= 9), it resulted in a smooth motion preceded by a sudden jump (we will term this as stick-jump-follow phenomenon); the staircase pattern is absent.

To summarize, stiction or static friction can lead to two different behaviors depending on the rate at which the input pressure is applied. In a closed loop, the input rate depends on the controller settings. A detuned controller is more likely to make the valve stick-slip repeatedly as low velocity motion occurs. This is depicted in Figure 2b. It is also worth mentioning that equation 2 is discontinuous at zero-velocity. The results presented here are obtained using the implementation suggested by [5] with a velocity tolerance of 1e-3.

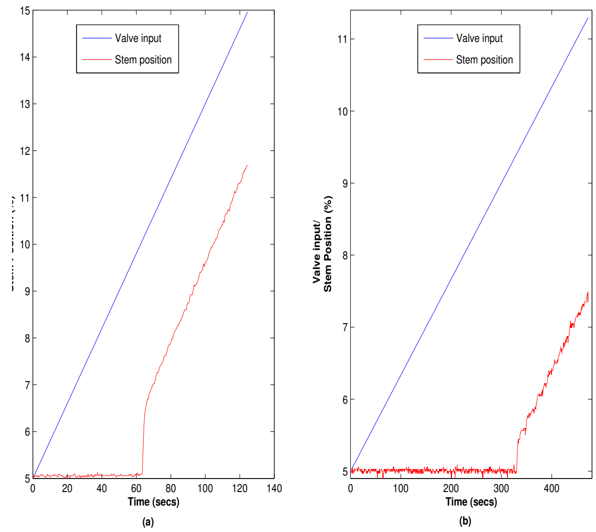

Fig. 3. Valve and stem position for a ramp input with slope (a) 0.0667%/sec and (b) 0.0167%/sec. A change in valve behavior can be noticed in (b).

III. Valve behavior - Experimental and industrial results

A. Laboratory level control loop

The control valve is a Anderson Hi-Flow Lin-E-Aire 1/2" valve (VA2000-32-220). To begin with the control valve exhibited negligible static friction ($< 0.2\%$). A static friction of about 5% of controller span (0 to 100%) was introduced in the valve by over-tightening the stem packing. A Linear Variable Differential Transformer (LVDT) (1000 DC-SE Schaevitz sensors) was installed to measure the stem position.

The level loop was put in manual and the valve input is ramped from 5% to 15% with different ramping slopes. Figures 3 and 4 show the stem position measurement for four different input slopes 0.0667%/sec, 0.0167%/sec, 0.0125%/sec and 0.01%/sec.

It can be seen from Figures 3a and 3b that for higher ramp inputs, the stem behavior is similar to the one expected from the mechanistic valve model (see Figure 2c). The valve overcomes the static friction and a sudden slip, followed by input tracking, with no further stick phase is observed. However, when the input to the valve is ramped at a slower rate, the valve after overcoming stiction slips and sticks again (see Figure 4). This is typical behavior predicted by the mechanistic model at low stem velocity (see Figure 2b).

B. Industrial flow loop

A flow loop in a refinery unit in India was considered to test the valve characteristics. The loop was put in manual and a ramp input was given at the OP. The stem measurement was not available. The data for the loop are plotted in Figure 5. It is evident that the valve exhibits a staircase behavior at low velocities. As the valve input is ramped up, the valve slipped and was stuck again. It can be seen that the slip jump and the stick band varied over the stem position. During the time period between 400 to 500 sample instants, the valve slip behaviors were very different indicating that indeed the valve behavior is complex to capture.

IV. Summary

Although the mechanistic model is representative of real valve behavior, a careful observation of Figures 3 and 4 reveal the following interesting observations:

1) The slip jump varied with the rate at which the valve input was given.
2) The dynamic friction (or coulomb friction) varied over the stem range. This is evident from Figures 4a, 4b, and 5.

All the above observations indicate that the valve friction phenomenon is complex and difficult to model. The classical model which implicitly models low and high velocity motions of a valve has to be modified to accommodate the stem position dependent nature of the friction forces. Through this modification, the mechanistic model can capture all the nonlinear characteristics of a valve in the presence of stiction. However, building such a model is complex and the modeling effort needs to be justified. To reduce the modeling effort, simple

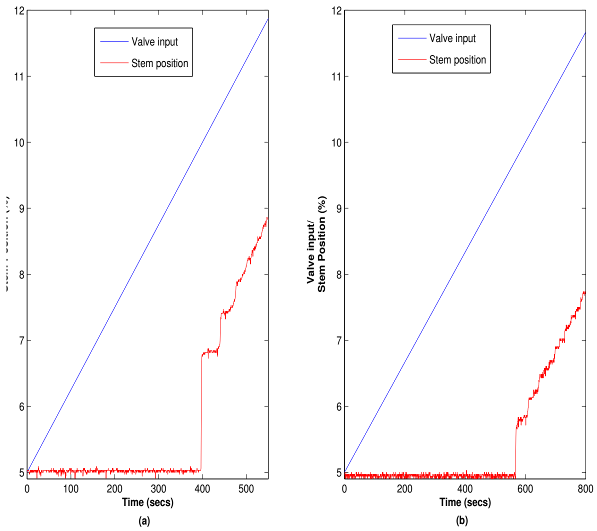

Fig. 4. Valve and stem position for a ramp input with slope (a) 0.0125%/sec and (b) 0.01%/sec. Stair-case behavior is observed.

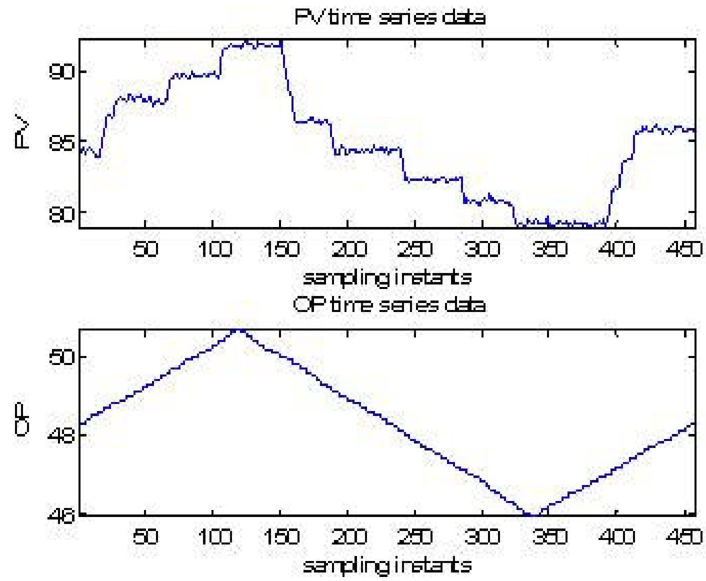

Fig. 5. Ramp test on an industrial flow loop (a) Measured Flow output (PV) (b) Ramp input at the valve (OP).

data driven models based on routine operating data have been proposed [2], [1] in the literature.

V. Data driven stiction models

Two basic empirical models can be found in the literature for modeling valve stiction:

1) A relay based model as given below was used to detect and quantify stiction [2].

$$x(t) = \begin{cases} x(t-1) & if\ |u(t) - x(t-1)| \le d, \\ u(t) & otherwise \end{cases} \quad (4)$$

Equation 4 is characterized by a single parameter 'd', termed as stiction band. Here x(t) and x(t-1) are past and present stem movements, u(t) is the present controller output. The stem moves from one position to the other once it overcomes the dead band 'd'.

2) A two parameter model that characterizes the static friction and the slip jump behavior explicitly unlike the relay model was proposed by [1].

The two models have a subtle but an important difference:

- The relay type model can capture staircase type nonlinear phenomenon of valves (see Figures 2b, 4b and 5). However, this model cannot capture phenomena such as the ones shown in Figures 2c and 3(a & b). Also the basic assumption of this model is that stiction is prevalent all along the stem range and the slip jump and static friction are equal to the stiction band 'd', which is not true in practice (see section III).
- Valve behavior such as the ones depicted in Figures 2c, 3 can be adequately modeled using the two parameter model proposed by [1]. However, this model cannot capture the repetitive stick-slip (staircase pattern) behavior for an increasing/decreasing ramp. This is because, in the model proposed by [1], for the stem to stick again, the valve input has to remain constant for more than two consecutive instants, which is not the case for the valve inputs shown in Figures 2b and 4.
- An important aspect that is not captured by both the models is the input rate dependent behavior of the valve.

A. *Discussion on the data driven stiction models*

A comprehensive data based model must encompass the following:

1) Dead-band.
2) Input rate dependence:
   - Stiction phenomenon 1: Stick phase, Slip phase, after which the stem follows the input at high stem velocities.
   - Stiction phenomenon 2: Stick-slip cycle due to low velocity motion.
3) Friction forces as a function of the stem position.

A model that can accommodate these behaviors is given below:

$$
x(t)=\begin{cases}
x(t-1) & if\ \Delta x(t-1)\ =\ 0 \\
 & \&\ |u(t)-x(t-1)|\ \leq\ sb \\
x(t-1)+sgn(\Delta u(t))sj & if\ \Delta x(t-1)\ =\ 0 \\
 & \&\ |u(t)-x(t-1)|\ >\ sb \\
x(t-1) & if\ \Delta x(t-1)\ \neq\ 0 \\
 & \&\ sgn\Delta u(t)=sgn\Delta u(t-1) \\
 & \&\ \mid \Delta u(t)\mid <\ r \\
x(t-1)+\Delta u(t) & if\ \Delta x(t-1)\ \neq\ 0 \\
 & \&\ sgn\Delta u(t)=sgn\Delta u(t-1) \\
 & \&\ |\Delta u(t)\mid\ \geq\ r \\
x(t-1) & if\ \Delta x(t-1)\ \neq\ 0 \\
 & \&\ sgn\Delta u(t)\neq sgn\Delta u(t-1)
\end{cases}
$$

$$
where\ <sb,\ sj>\ =\ f(x,\Delta u). \quad (5)
$$

Here *sgn* indicates the sign of the argument, *sb* represents the valve dead-band and stick-band, *sj* represents the stick jump. Δu represents the change in valve input u, Δx represents the change in stem position, r represents the slope below which a staircase behavior is observed and the parameters *sj* and *sb* are dependent on the stem position and input velocity. The first two conditions pertain to the stick-slip motion when the valve is at rest. The third and fourth conditions capture the velocity dependent behavior of a valve in motion. The last condition captures the effect of the valve reversal.

The proposed data based model has three parameters. The stem position dependent nature of sj and sb may have to be relaxed for practical purposes as it may be difficult to obtain them for each of the industrial valves. Under this assumption, a methodology as given in [6] can be modified to identify these three parameters.

In industrial settings the control valves usually operate under closed loop conditions. Under closed loop, the valve behavior is confined to a small operating region (due to regulatory nature of the control loop) and the valve behavior can be safely assumed to be independent of the stem position until a set-point change moves it to a different operating regime. This is also evident from the stem position measurement shown in Figure 6, where a level loop limit cycles due to stiction and the stem jumps to a new position once the controller overcomes the stiction band (d = 5.1%). Under closed loop conditions, it has been adequately shown in [6] that a simple one parameter model as given in equation 4 may be sufficient. Also it was further shown in [7] that stiction compensation signal under closed loop can be calculated by using the simple stiction model.

In the next section the implications due to staircase type pattern under low velocity motion in closed loop conditions is illustrated through a describing function analysis.

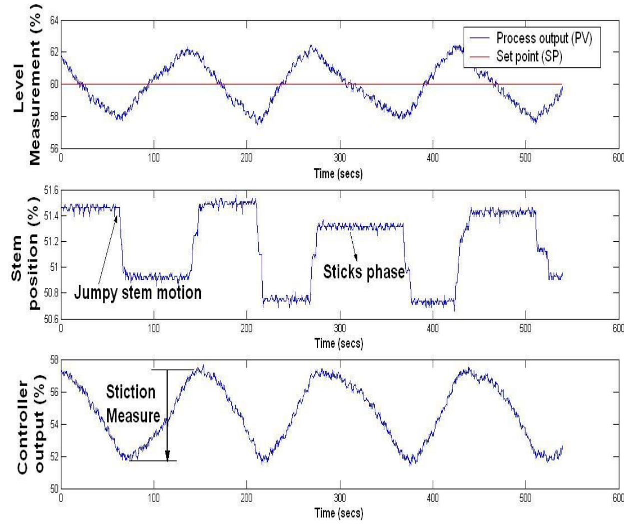

Fig. 6. Closed loop behavior of a self-regulating level loop in presence of stiction (d = 5.1%).

B. Describing function for Stiction non-linearity

In this section, it is assumed that the control valve under study exhibits a staircase behavior for an increasing (or decreasing) input. For simplicity, the describing function for this stiction nonlinearity is derived using the simple model given by equation 4. The describing function for stiction nonlinearity is then given in equations 6 and 7:

$$
n_p=\begin{cases}
0 & if\ A<d/2 \\
\frac{2d}{\pi A}\left(\sqrt{(1-\frac{d}{2A})^2}\right) & if\ \frac{d}{2}\leq A<\frac{3d}{2} \\
\frac{2d}{\pi A}\left(\sqrt{(1-\frac{d}{2A})^2}+\sqrt{(1-\frac{3d}{2A})^2}\right) & if\ \frac{3d}{2}\leq A<\frac{5d}{2}
\end{cases} \quad (6)
$$

$$
n_q=\begin{cases}
0 & if\ A<d/2 \\
-\frac{d^2}{\pi A^2} & if\ \frac{d}{2}\leq A<\frac{3d}{2} \\
-\frac{3d^2}{\pi A^2} & if\ \frac{3d}{2}\leq A<\frac{5d}{2}
\end{cases} \quad (7)
$$

where ‘d’ represents the stiction band d.

For a ramp input, the quantizer and the simple stiction model given by equation 4 seem to give a similar output as suggested in [8]. However there exists one important difference between a quantizer and the simple stiction model. Quantizer is a memory independent (or memoryless) nonlinearity, whereas the simple stiction model depends on the past input. This leads to a non-zero imaginary part (see equation 7) in the describing function for the stiction model. This describing function for the staircase pattern can lead to multiple limit cycles.

C. Multiple limit cycles - Simulation example

A control loop with plant $G_p = \frac{1}{5s^2+6s+1}$, controller $G_c = \frac{0.1s^2+0.5s+1}{s}$ is considered for simulation study. Stiction nonlinearity with a stiction band d = 0.5 was introduced using the simple stiction model given by equation 4.

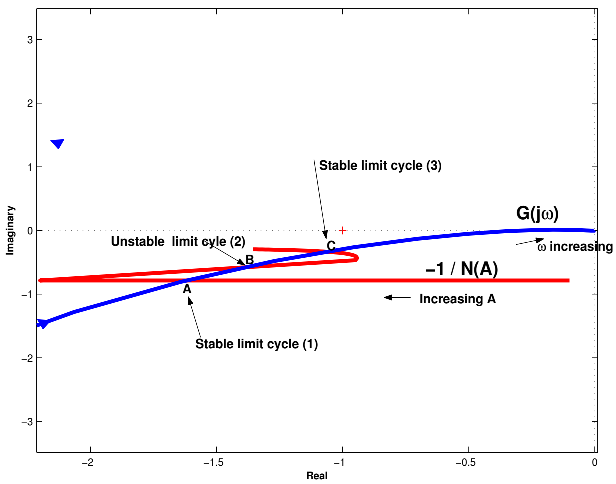

Fig. 7. Limit cycle detection using Nyquist stability plot for the simulation system. Nyquist plot of G_pG_c system in blue and negative inverse of N(A) in red.

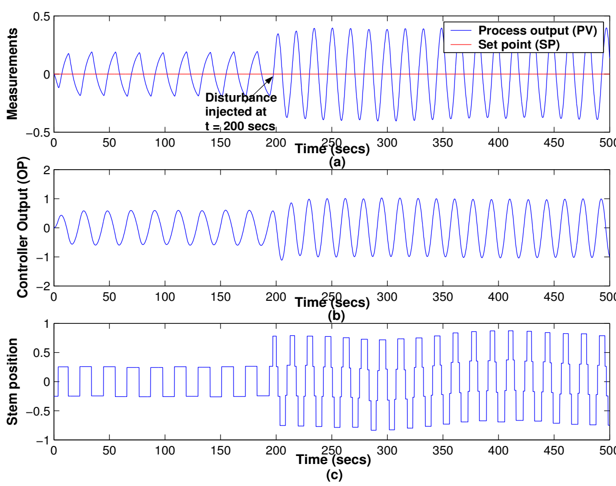

Fig. 8. Multiple limit cycle oscillation occurs when a disturbance was injected at time instant t = 200. (a) Process output and set-point (b) Controller output and (c) stem position. As seen when the limit cycle switches to other state, the stem sticks twice in the same direction.

The Nyquist plot for the linear system (G_pG_c) along with the $\frac{-1}{N(A)}$ plot for stiction non-linearity is shown in Figure 7. It is seen from Figure 7 that the system has three limit cycles A, B and C. The limit cycles A and C are stable and the limit cycle B is unstable.

Figure 8 shows the presence of two limit cycles when a disturbance was injected at time instant t = 200 secs. After injecting the disturbance, the system moved from one stable limit cycle point (A) to the other stable limit cycle point (C). This example demonstrates the possibility of multiple limit cycles occurring in control loops.

VI. Conclusion

In this paper it is shown through simulation and experiments conducted in an industry and laboratory that valves like any other mechanical system is dependent on the rate at which it is opened or closed. Comprehensive modeling of valve stiction is a complex task. Low velocity motion of a valve can lead to a staircase pattern for a ramp input. However, this is not seen when the valve is operated at a higher velocity. It was shown that existing data driven models need to be modified to capture the complexities of the stiction phenomenon that occur under open loop conditions. In view of this, the need for a modified data driven model was highlighted and a three parameter model was suggested. Further work to validate this three parameter model is under progress. Ultimately these more sophisticated data based models might be more useful for simulation studies; while for detection and compensation under closed loop regulatory conditions, simpler models may be adequate.

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