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A Sigmoid Function based Method for Detection of Stiction in Control Valves

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Abstract— **Sticky control valve induced oscillations are the most common source of deteriorated control loop performance. Although there are many stiction detection algorithms, complexity remains as the top reason for their restricted applications. This work proposes a new method to detect malfunctioning control valves (due to stiction) in process control loops. The proposed method embroils in fitting a sigmoid function (or logistic function) to OP (controller output) and ΔPV (change in process variable (PV)). Effectiveness of the method is assessed by application to industrial control loops belonging to a wide variety of industries. Results demonstrate that the method can compete with the existing methods while being simple in applications.**

I. Introduction

Safe and optimal process operation is the chief objective of process industries. Oscillating control loops can often be the roadblocks in accomplishing the above stated objective [1]. Oscillations in these control loops can be triggered by improper controller tuning, sensor malfunctions, process upsets and control valve faults. Among the control valve faults, valve stiction is considered the most frequent cause of fluctuations in closed loops signals [2]. In the last two decades, significant efforts were made towards the development of manual (or invasive) and automatic (non-invasive) methods. In order to employ the invasive methods, control valves are required to be taken out of operation, which may interrupt running plant. Owing to this disadvantage, the non-invasive methods received more attention from researchers and practicing engineers. The existing non-invasive methods depend on limit cycles, waveform shapes, nonlinearity detection, statistical and machine learning algorithms, and optimization methods. The complete details of the existing methods can be found in [3-6].

The presence of triangular, square or sinusoidal waveforms in oscillating OP or PV is a prerequisite for the application of most shape-based methods [7-11]. Sampling rate, mean-nonstationary, oscillation persistency and noise can damage the waveform shapes. In addition, the incidence of stiction and one or more of the non-stiction conditions simultaneously affecting a control loop can also distort the waveform shapes. If the waveform shapes are not clearly conspicuous owing to the issues mentioned above, the shape-based methods might yield false alarms. Because of this fact, the shape-based methods lack wide applicability. Unlike them, butterfly-shape based method (BSD) proposed in [12] does not rely on the waveform shapes but instead looks for a butterfly-like shape in a phase plot drawn with modified PV and OP. When all of these methods were applied to benchmark industrial control loops available in international stiction database (ISBD) created by [3], the BSD method demonstrated superior stiction detection performance. However, as pointed out in [4], the BSD method may not work well outside ISDB. This research gap enthused the authors of the present work to propose a new shape-based method. The enthralling characteristics of the proposed method are furnished below.

- Only OP and PV signals are required to detect stiction.
- It works in an unsupervised way. No explicit training is required.
- It is applicable to stationary and non-stationary signals.
- It provides clear and straightforward results regarding the root cause of a given oscillating control loop.
- It can recognize sticky valves even if PV and OP have multiple oscillations.
- It can be applied to flow, temperature, concentration, pressure and analyzer related control loops.

The rest of the paper comprises four sections. In Section II, the generic behaviour of a sticky control valve is explained. The proposed method is described in Section III. In Section IV, the method is applied to industrial case studies. In Section V, the paper is concluded.

II. Control Valve Stiction

The generic nature of a control valve affected by stiction is illustrated in Fig. 1. Owing to the existence of stiction, OP is nonlinearly related to valve position instead of a linear relation that is the case with a healthy valve. PV and OP of flow loop are shown in Fig. 2 [3]. The characteristic curve displayed in Fig. 1 contains four unique phases: deadband, stickband, slip-jump and moving phase. During stiction, the valve stem stays at a constant value while OP is moving from point A through point C. Because of this, process input does not change, causing process variable (PV) to remain constant or vary slowly. This steady state phase in PV lasts as long as the valve stem does not budge. Therefore, an offset is created between PV and setpoint (SP), which forces controller to vary OP. When cumulative change in OP is sufficient to push the

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valve out of stiction, the valve stem position abruptly jumps from point C to point D, which is termed the slip-jump. From point D onwards, the valve moves without pause (moving phase) so that both OP and PV change. When PV deviates from SP, the controller changes OP in an effort to bring PV back to SP. When OP starts decreasing (at point E), the valve sticks again. For a given time period, the valve may stick several times; consequently, PV intermittently reaches steady state (or pseudo steady state because of noise). Figure 3 portrays the oscillating PV and OP of concentration control loop having a healthy valve. Since a non-stiction condition (inappropriate controller tuning) gives rise to the oscillations and the valve is free of stiction, PV and OP continuously vary.

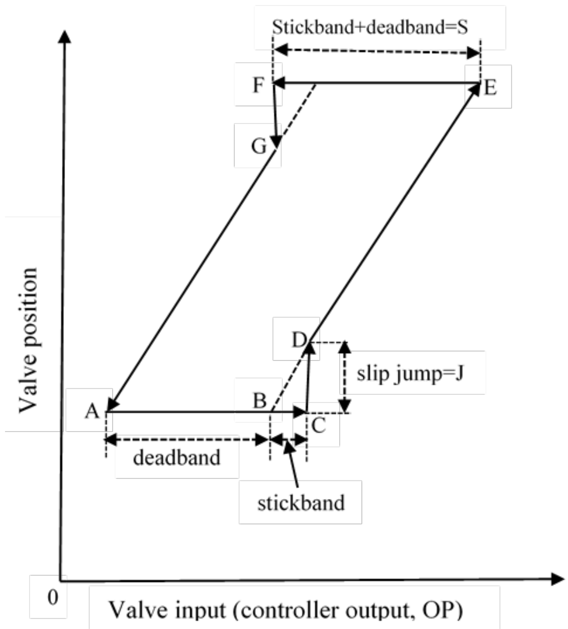

Figure 1. Behaviour of control valve with stiction [5]. Here, S is called stiction band.

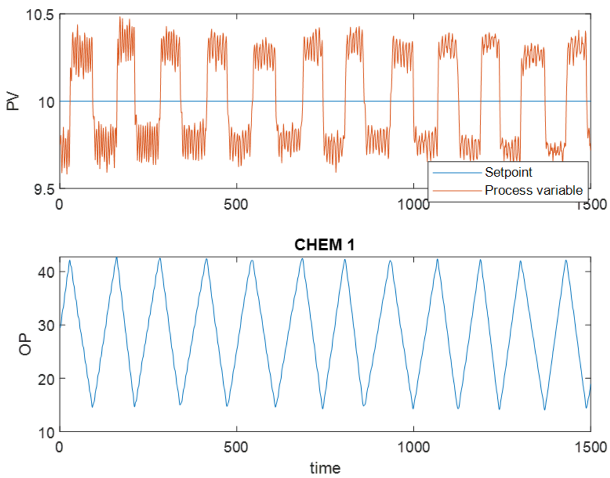

Figure 2. Flow control loop with a sticky control valve [3].

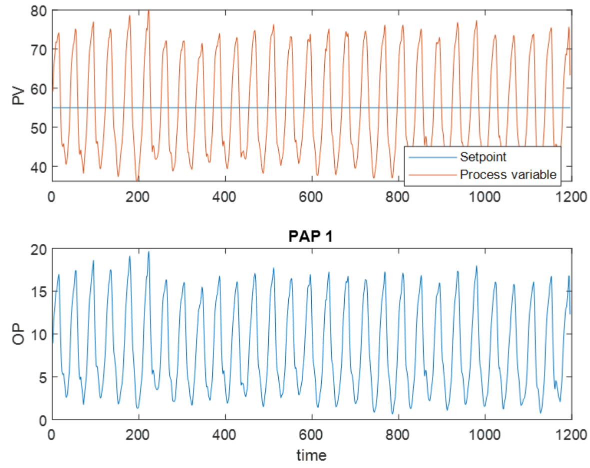

Figure 3. Concentration control loop with a healthy valve [3].

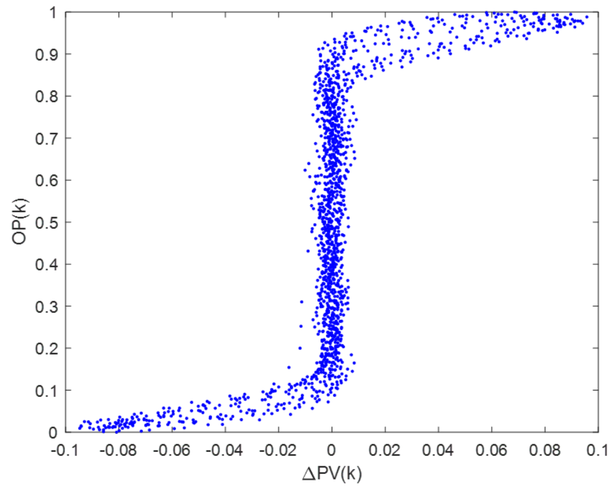

Figure 4. Phase plot of the flow loop. Here, $\Delta PV(k) = PV(k+1) - PV(k)$ and k denote time instant.

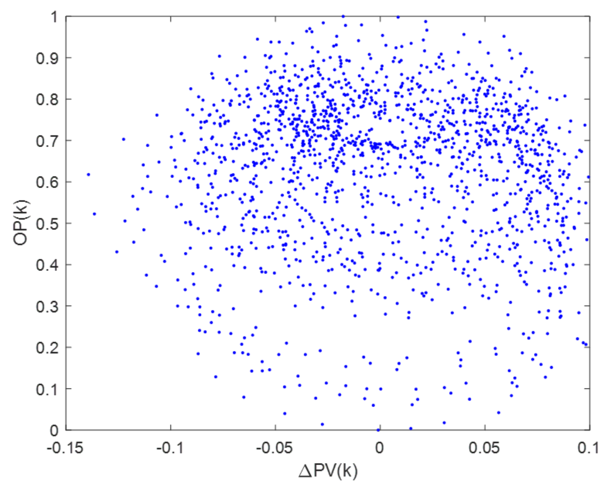

Figure 5. Phase plot of the concentration loop

III. THE PROPOSED METHOD

The main idea behind the proposed method is that if the oscillations in a given control loop are brought out by stiction, then the $OP(k)$ vs $\Delta PV(k)$ phase plot will have an s-like shape (or sigmoid-like curve). To make the idea clearly comprehensible, let us consider the closed loop signals (OP and PV) of the flow loop depicted in Fig. 2. The control valve in the flow loop is actually sticky and gives rise to the oscillations. According to Fig. 4, the shape in the phase plot drawn for this flow loop resembles sigmoid curve. When $\Delta PV(k)$ accepts values in a small neighborhood of zero, the curve becomes linear (almost straight line). This linear behaviour of the curve is instigated by the sticky phase of the control valve. When the stem position remains unchanged, PV either ceases to change or experiences small variations. $\Delta PV(k)$ computed during stiction becomes very small (i.e. close to zero) whereas $OP(k)$ keeps changing. That is why the curve exhibits linear behavior in the vicinity of $\Delta PV(k)=0$. The appearance of the s-like shape in the phase plot is a sole characteristic of a sticky control valve. When there is no stiction and the oscillations are induced by any non-stiction condition, according to Fig. 5, the phase plot has a different shape. The phase plot can visually be examined to confirm presence of the sigmoid-like curve. However, diagnosis made via this approach is highly subjective. To get more reliable results automatically, sigmoid function (or logistic function) can be used.

The sigmoid function is delineated by the following equation.

$$y=\frac{1}{1+\mathbf{e}^{-(ax+b)}} \tag{1}$$

where a and b are unknown parameters.

For $a=1$, $b=0$ and $x\in[-10,10]$, the sigmoid function produces the standard sigmoid curve (shown in Fig. 6), to which the shape in Fig. 4 is akin. Hence, stiction detection reduces to fitting the sigmoid function to the data $(x,y)=(\Delta PV(k),OP(k))$. To determine the unknown parameters: a and b, the following optimization problem can be solved using trust-region-reflective algorithm.

$$J=\underset{a,b}{\mathbf{min}}\left(\frac{1}{N}\sum_{k=1}^{N}\left(y(k)-\tilde{y}(k)\right)^2\right) \tag{2}$$

where $y(k)=OP(k)$, $\tilde{y}(k)$ is the output of Eq. (1) and N is the length of the PV or OP signal.

Once the sigmoid function is fitted to the data, correlation coefficient defined in Eq. (3) can be computed.

$$R=\frac{\mathbf{cov}(Y,\tilde{Y})}{\sigma_Y\sigma_{\tilde{Y}}} \tag{3}$$

where $\mathbf{cov}(Y,\tilde{Y})$ is the covariance between Y and $\tilde{Y}$ vectors, σ_Y and $\sigma_{\tilde{Y}}$ are the standard deviations of Y and $\tilde{Y}$, respectively, $Y=[y(1),y(2),....,y(N)]$ and $\tilde{Y}=[\tilde{y}(1),\tilde{y}(2),....,\tilde{y}(N)]$.

If $R\geq R_{threshold}$, the control valve is sticky. The proposed method is summarized below.

Step 1: Compute ΔPV (first order backward difference of the PV signal).

Step 2: Fit the sigmoid function to the data $(\Delta PV,OP)$.

Step 3. Compute R using Eq. (3). If $R\geq R_{threshold}$, then stiction is the actual cause of oscillations. Otherwise, any of non-stiction conditions may be the culprit of poor control loop performance.

The previously mentioned three steps are repeated for each oscillating control loop.

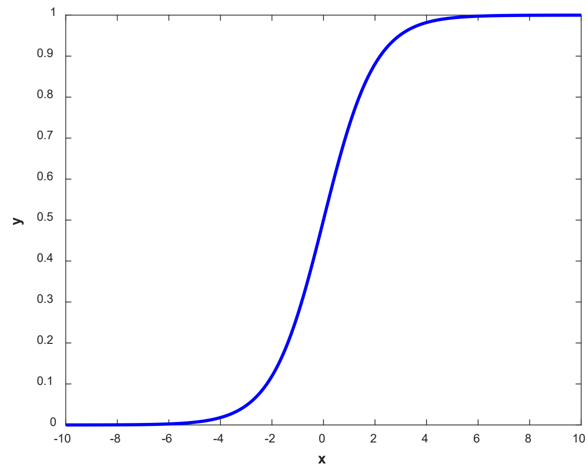

Figure 6. Standard sigmoid curve (or logistic curve)

IV. APPLICATION TO INDUSTRIAL CONTROL LOOPS

Jelali and Huang (2009) open sourced a database (ISDB) having closed loop signals of several control loops. ISDB is useful to examine the performance of new methods [3]. Twenty control loops from ISDB were considered in this work. All of them exhibit cycling behaviour. Apart from these control loops, two flow control loops were adopted from an oil sands industry to verify whether the proposed method works beyond ISDB. $R_{threshold}$ was chosen to be 0.5 and the same value was used for every control loop examined in the present work.

A. Benchmark Control Loops

Results for the twenty control loops are provided in Table I. Figs. 7 and 8 present the phase plots of representative control loops. According to Table II, the proposed method delivered acceptable stiction detection performance in the benchmark industrial control loops. As per the comparison shown in Table III, the proposed method outperformed all of them except BSD. The number of correct diagnoses achieved via the proposed method and BSD is the same. In the succeeding subsection, it will be shown that the proposed method holds wider applicability than BSD.

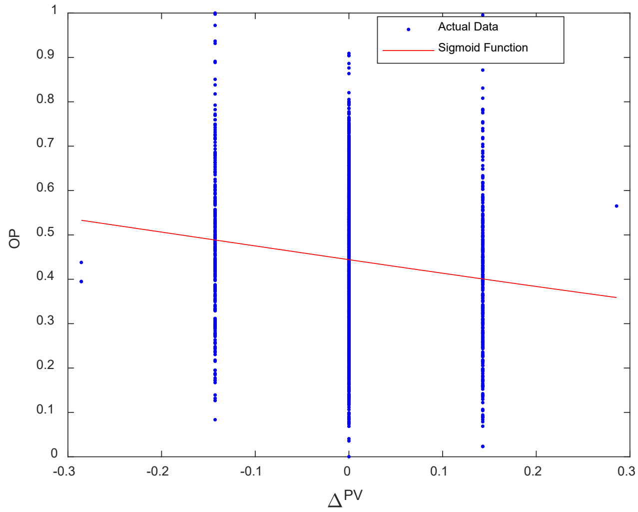

Figure 7. Phase plot of CHEM 3

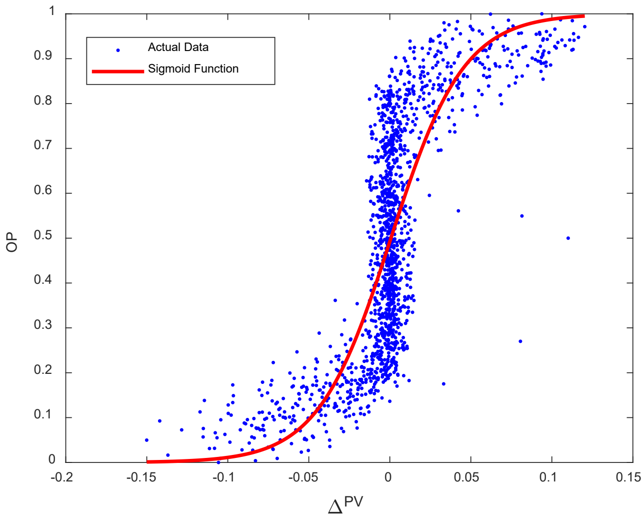

Figure 8. Phase plot of CHEM 24

B. *Control Loops from an Oil Sands Industry*

To verify if the proposed method and BSD work in not only the benchmark control loops but also other control loops, two industrial flow control loops (Figs. 9 and 10) from the oil sands industry were considered. Both loops have a sticky control valve. Figs. 11 and 12 show results of the proposed method while Figs. 13 and 14 show the results of the BSD method. In agreement with Figs 13 and 14, the BSD method failed to provide correct diagnosis for both the control loops because the shapes in those figures do not look like a butterfly. Inversely, the proposed method successfully recognized stiction. This emphasizes that the proposed method can have more industrial application potentials than the BSD method.

TABLE I. RESULTS FOR THE 20 BENCHMARK CONTROL LOOPS

Loop Name	Control Loop	Actual Malfunction	R	IDC?
CHEM 1	FC	Stiction	0.78068	Yes
CHEM 2	FC	Stiction	0.4501	No
CHEM 3	TC	Non-stiction	0.1479	Yes
CHEM 6	FC	Stiction	0.298	No
CHEM 10	PC	Stiction	0.7683	Yes
CHEM 11	FC	Stiction	0.7913	Yes
CHEM 12	FC	Stiction	0.6098	Yes
CHEM 13	AC	Non-stiction	0.05314	Yes
CHEM 14	FC	Non-stiction	0.2062	Yes
CHEM 16	PC	Non-stiction	0.6991	No
CHEM 23	FC	Stiction	0.7533	Yes
CHEM 24	FC	Stiction	0.7846	Yes
CHEM 29	FC	Stiction	0.5988	Yes
CHEM 32	FC	Stiction	0.5511	Yes
PAP 2	FC	Stiction	0.7802	Yes
PAP 4	CC	Non-stiction	0.0475	Yes
PAP 5	CC	Stiction	0.8755	Yes
PAP 7	FC	Non-stiction	0.0866	Yes
PAP 9	TC	Non-stiction	0.1249	Yes
MIN 1	TC	Stiction	0.5329	Yes

IDC-is diagnosis correct, CHEM–chemicals, PAP–pulp and papers, MIN – mining, FC – flow control, TC – temperature control, PC – pressure control, AC – analyzer control, CC – concentration control,

TABLE II. PERFORMANCE OF PROPSOED METHOD

Performance Metric	Value
True positive	11
True negative	6
False positive	1
False negative	2
Precision	0.9167
Recall	0.8462
Specificity	0.8571
F1 score	0.88
Accuracy	0.85

TABLE III. COMPARISON WITH EXISTING METHODS

Stiction Detection Method	Number of Correct Diagnoses
Proposed method	17
BSD [12]	17
KMW [4]	16
CNN-PCA [13]	16
BIC [14]	16
SDN [15]	15
HAMM2 [3]	15
HAMM3 [3]	14
CORR [16]	13
HIST [17]	13
RELAY [18]	13
ZONE [10]	13
CURVE [19]	12
SLOPE [10]	12
NLPCA-AC [20]	11
AREA [11]	10

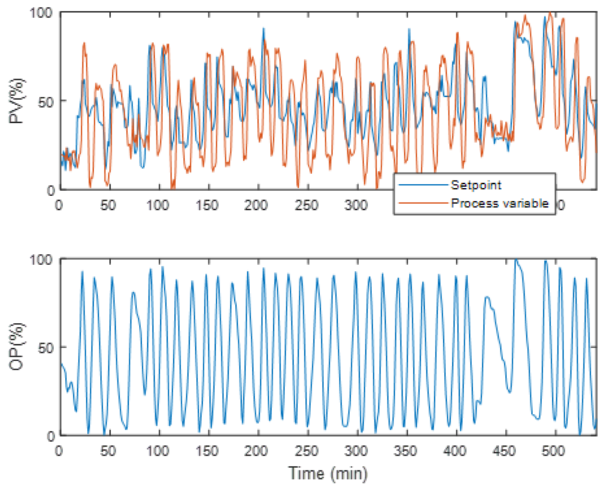

Figure 9. Flow loop 1 from the oil sands industry.

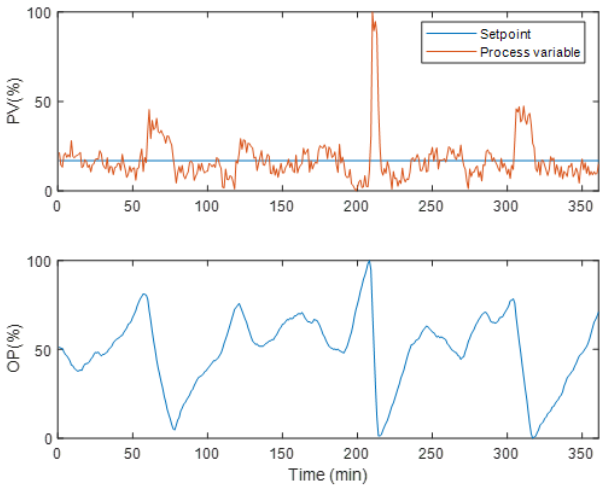

Figure 10. Flow loop 2 from the oil sands industry.

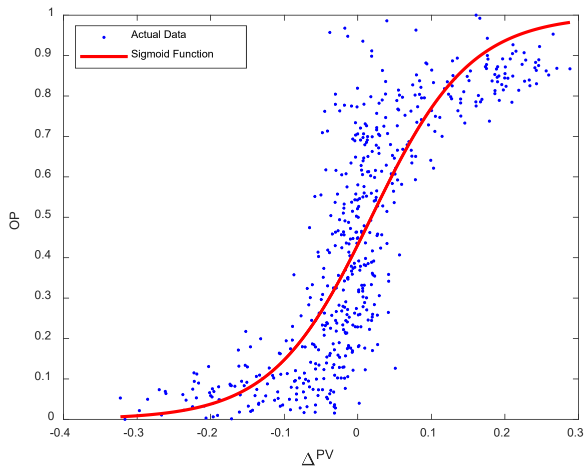

Figure 11. Phase plot of flow loop 1 from the oil sands industry. Correlation coefficient obtained is $R = 0.8401$.

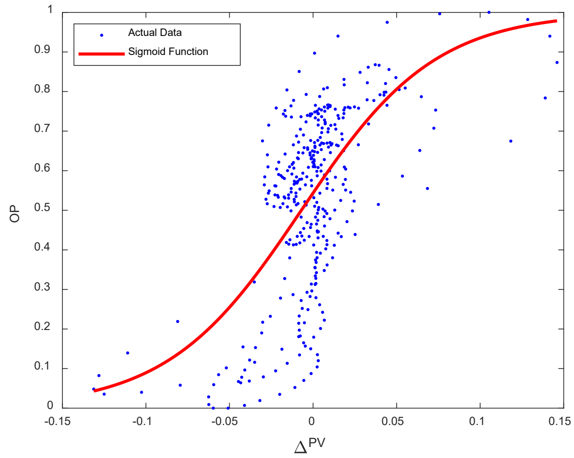

Figure 12. Phase plot of flow loop 2 from the oil sands industry. Correlation coefficient obtained is $R = 0.6262$.

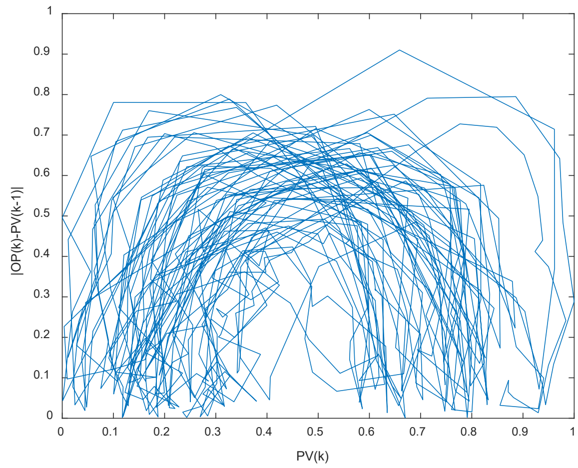

Figure 13. BSD plot for flow control loop 1 from the oil sands industry.

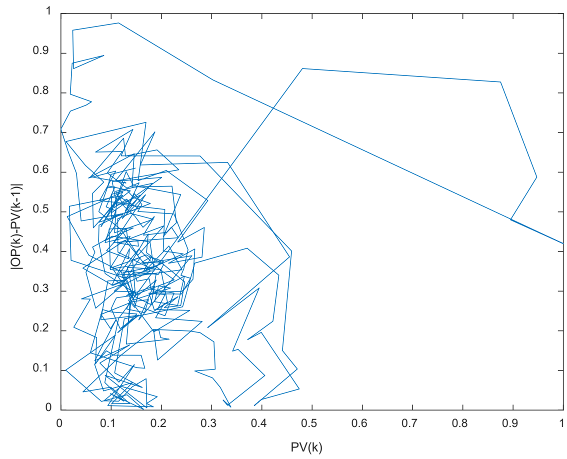

Figure 14. BSD plot for flow control loop 2 from the oil sands industry.

V. CONCLUSION

Control loops with sticky valves often contribute to production loss and reduced profits. It is important to identify sticky control valves in a timely manner. In the current work, a simple shape-based method was developed and tested in the industrial control loops. The proposed method demonstrated a satisfactory stiction detection performance, and owns wider applicability potentials compared to the existing shape-based methods.

Stiction quantification can be useful to timely remind panel operators to take immediate action and prevent potential process upset whenever possible. It also helps maintenance engineers to plan plant shutdowns to repair or replace the faulty valves. In our future work, deep learning based methodology will be formulated to estimate stiction band.

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