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Practical Linear Regression-Based Method for Detection and Quantification of Stiction in Control Valves

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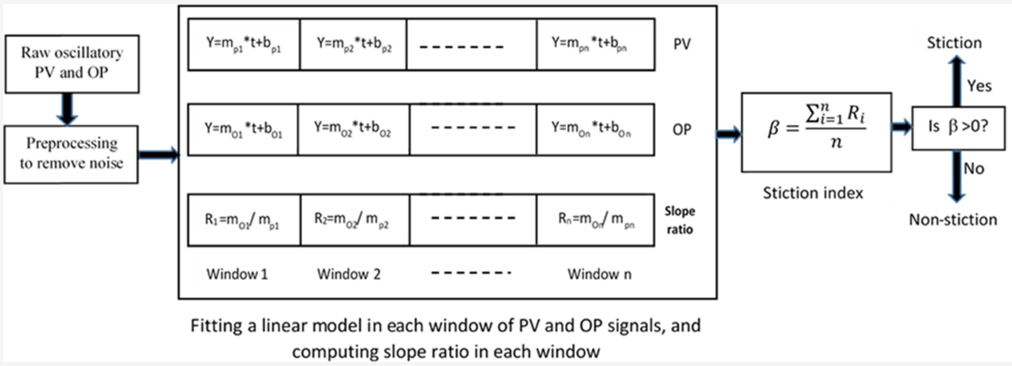

ABSTRACT: Control valve stiction is constantly encountered by virtually all process industries on a regular basis. Valve stiction is a menace to the safe and economically optimal operation of the process industries. In the present work, a novel data-driven method is developed to detect sticky control valves in industrial control loops. The rudimentary concepts of statistics are the foundation of the developed method. Rigorous testing of the proposed method in control loops pertaining to a wide variety of process industries demonstrates superior stiction detection capability over most of the existing methods. Apart from stiction detection, the proposed method offers estimation for a stiction band to assist maintenance engineers to schedule plant turnarounds in advance. Furthermore, the method is capable of detecting a faulty control valve in industrial control loops.

1. INTRODUCTION

Process industries operate at high efficiency, by optimally utilizing raw materials and energy, to meet strict product specifications and withstand market competition while obeying stringent environmental regulations. Automation systems (or industrial automation), which employ feedback control loops, assist the process industries in achieving these goals. In a feedback controller, an error signal is generated from the difference between the desired (setpoint) and the measured (actual) value of a key process variable (PV). Based on the error signal, the feedback controller calculates a change command (% valve open) that manipulates process input to cause PV to more closely track the setpoint. The change command signal produced by the controller is actually implemented by the control valve (final control element). According to the controller output (OP), the control valve alters its stem position to change the flowrate of a medium (liquid, gas, or slurry) flowing through the valve. The control valve is an important component, and its performance strongly affects the control loop. In an effort to put control commands into effect, the control valve strokes several thousand times a day. As a result, it is subject to frequent wear and tear. Therefore, in-service control valves develop faults over time, which affects the normal operation of valves and subsequently degrades control loop performance. Paulonis and Cox,[1] Desborough and Miller,[2] and Bialkowski[3] and Ender[4] conducted an extensive survey on over 26 000 proportional integral derivative (PID) control loops and found that a significant number of control loops demonstrated poor performance, of which 20−30% experienced oscillations due to control valve stiction. Stiction offers resistance to proper valve movement and introduces a delay between controller output and valve stem position. Stiction in control valves can be caused by tight packing around the valve stem, deposition of foreign particles in between the valve stem and packing, depletion of lubricant, seal degradation, etc. In practice, stiction is often measured as a percentage of OP span (0−100).[5]

In process industries, mild valve stiction (i.e., less than 0.2%) may not be troublesome to some degree, but severe stiction

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can cause equipment trips, equipment outages, or even unscheduled plant shutdown. Severe control valve stiction may transpire sporadically, but a single incident can induce a huge performance as well as economic loss. Therefore, it is of paramount importance to detect stiction in control valves to avoid major disruptions to plant operations, which can potentially happen if stiction is not detected timely. Detection of sticky valves in control loops has always been an active research topic. During the last two decades, a spate of methods has been put forward from diverse viewpoints. The existing methods can be categorized into invasive (manual) and noninvasive (automatic) methods. The invasive methods can detect stiction at ease but require control valves being tested to be taken out of operation during testing.[6−9] In addition, they need expert engineers to perform the tests, which are expensive and time consuming. On the contrary, automatic methods can analyze the behavior of control valves while they are in operation. Once plant maintenance engineers find sticky control valves, they carry out the following actions depending upon the severity of stiction. If stiction is small, the sticky control valves may still be in automatic or cascade mode but respective controllers need retuning. In this situation, the performance of control loops gets decreased. If stiction is abstemiously large, the sticky control valves are put in a manual operation model (i.e., plant operators manually adjust feed flowrate) until the valves are repaired or replaced. If stiction is very large, the sticky control valves need immediate service. Jelali and Huang,[5] Zheng et al.,[10] and Bacci di Capaci and Scali[11] provide a thorough and comprehensive discussion of the existing automatic stiction detection methods.

1.1. Motivation and Contributions. Zheng et al.[10] compared the stiction detection capability of noninvasive methods, published from 2015 to 2020, in 20 oscillating control loops taken from the international stiction database (ISDB) formed by Jelali and Huang.[5] The 20 control loops were adopted from different industries and the real root causes for their unsatisfactory behavior are known. Table 1 reproduces the results obtained in Zheng et al.[10] The full forms for the acronyms shown in Table 1 are provided in Table S1 in the Supporting Information file.

This set of methods ranges from simple to complex. Nonlinear principal component analysis and autocovariance (NLPCA-AC) is based on an autoassociate neural network and its performance is inferior to that of much simpler methods: ZONE, SLOPE, CURVE, and K-means clustering based 94 moving window (KMW). Quite the opposite, ZONE, SLOPE, and CURVE could not outperform intricate methods such as stiction detection network (SDN), Hammerstein-model based 97 method (HAMM)2, and HAMM3. An important point that needs to be comprehended is that when a method is simple, it is not able to provide increased correct diagnosis, whereas some methods can issue correct verdicts in most of the control loops but at the price of less interpretation and more complexity. Only butterfly shape-based detection (BSD) and KMW seem to have achieved a reasonable trade-off between simplicity and effectiveness. Even BSD is prone to noise in PV and OP signals. As is well known, industrial applications are in favor of simple-to-use methods, which can be easily implemented in a distributed control system and provide reliable results. This fact motivated the authors of the present work to bring forward a much simpler stiction detection method (simpler than BSD and KMW), which demonstrates comparable and/or better performance than most of the methods shown in Table 1 and owns all essential qualities to be adopted by the industries.

Table 1. Results of Existing Methods

stiction detection method	number of correct diagnosis
BSD[12]	17
KMW[10]	16
CNN-PCA[13]	16
BIC[14]	16
SDN[15]	15
HAMM2[5]	15
HAMM3[5]	14
CORR[16]	13
HIST[17]	13
RELAY[18]	13
ZONE[19]	13
CURVE[20]	12
SLOPE[19]	12
NLPCA-AC[21]	11
AREA[22]	10

The main contributions of the present work are listed below.

- A simple and effective data-driven method is proposed to detect sticky control valves in industrial control loops. The method relies on OP and PV signals, works in an unsupervised manner, and produces straightforward results, which need no further analysis.
- The proposed method also provides estimation for the stiction band.
- The proposed method exhibits a reasonable degree of robustness to noise in the OP and PV signals.
- In addition to identifying and quantifying valve stiction, the method recognizes faulty valves (unexpected valve closures or severe valve stiction) in industrial settings.
- To show the effectiveness of the proposed method, the method is rigorously tested in benchmark control loops and control loops adopted from an oil sands industry.

The remaining part of the paper is structured as follows. In Section 2, the limitations of related existing stiction detection methods are discussed. The behavior of a sticky valve is explained in Section 3. The theory of the proposed method is given in Section 4. Section 5 presents a discussion on the determination of optimum values of window size and threshold, performance evaluation, and robustness of the proposed method. In the last section, the paper is concluded.

2. LIMITATIONS OF RELEVANT EXISTING METHODS

The limitations of the existing methods that share some similarities with the method proposed in the present work are discussed in this section.

Florentino and Mariappan[23] patented a statistical quality control-based method: slope ratio (SR). In the SR method, reference period is defined, during which the slope of a regression line, in the scatter graph between OP on the abscissa and manipulated variable (MV) (pressure supplied to the control valve) on the ordinate, is computed. The reference period contains historical data of OP and MV, and these data are collected when the control valve is healthy. The target period is used to check the running status of the control valve and includes recent measurements of OP and MV. The ratio between the slopes obtained in the reference and target periods

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is calculated and compared with a prespecified threshold. If the ratio exceeds the threshold, then the control valve is declared faulty (stiction). The SR method is a bit analogous to the method proposed in the present work. However, the SR method possesses some limitations, which are pointed out in the following discussion.

- The SR method requires MV measurements. This is a great disadvantage because these measurements are seldom available in practice. This requirement needs an additional sensor, which increases the operating and maintenance costs of plants. Therefore, it is not a cost-effective approach. When MV measurements are not available, the SR method cannot be employed. Florentino and Mariappan[23] also raised the same concern in their patent.
- When the SR method is applied to OP and PV, there is a high chance that the method will yield erroneous results. Because even though the control valve is healthy in the target period, one or more of the nonstiction conditions (process upsets, sensor malfunctioning, and aggressive controller tuning) can take place at the same time, which also induces oscillations in the control loop. In this case, the SR method may indicate the presence of stiction, although the valve is healthy. The same is applicable to the reference period. If any nonstiction condition occurs in the reference period and the valve is currently sticky, the slope in the reference period may be equivalent or close to the slope in the target period. So the ratio will not exceed the threshold; hence, the SR method may generate false-negative alarms. This is because oscillations caused by nonstiction conditions are somewhat similar to oscillations induced by sticky valves.
- The SR method is, to some extent, a supervised learning method because it depends on the reference period to detect stiction in the control valve.

Dambros et al.[19] developed SLOPE and ZONE methods to detect stiction. In the SLOPE method, it is assumed that triangular shapes are present in the OP signal for self-regulating processes and in the PV signal for integrating processes. In each half-cycle of the OP or PV signal, the slope between the peak (or valley) and the point in the evaluation interval is computed. The mean of the absolute value of the obtained slopes is compared with the mean of the absolute value of slope calculated in each of the half-cycles of a reference triangular wave. Stiction is diagnosed based on the resulting difference. This method, too, possesses certain drawbacks explained as follows. The presence of a triangular shape in the OP or PV signal is a prerequisite to employing the SLOPE method. However, as one notices in the benchmark control loops, there is no guarantee that the closed-loop signals of a control loop having a sticky valve contain perfect or nearly triangular shapes. The triangular shape can be distorted by noise, the simultaneous occurrence of stiction and nonstiction conditions. When this happens, the SLOPE method will issue false alarms. Therefore, the SLOPE method, as seen from Table 1, is not always applicable.

3. CONTROL VALVE STICTION: A REVISIT

Figure 1 shows a characteristic behavior of a control valve affected by stiction. The response (MV) of the control valve to controller output (OP) comprises four distinct phases: deadband, stickband, slip-jump, and moving phase. When the

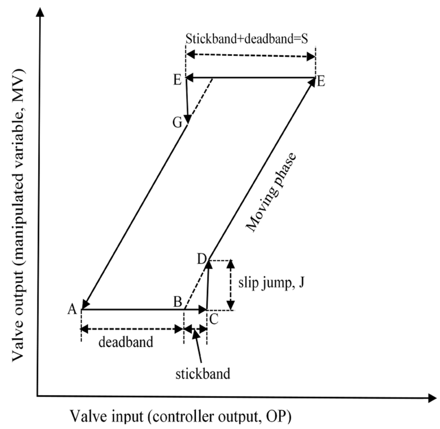

Figure 1. Signature plot of a control valve with stiction.[14]

control valve remains idle or changes its direction at point A, the valve stem does not move although OP keeps on changing in an effort to maintain PV at the desired value. Deadband and stickband together represent the dormant state of the control valve. The sum of deadband and stickband is defined as stiction band S. Once the controller generates driving force (OP) enough to move the valve, the valve overcomes stiction and suddenly moves; consequently, an abrupt change (jump from point C to point D) in MV takes place. The abrupt change in MV is represented by slip-jump. After point D, the valve moves unceasingly until point E, which is marked as the moving phase. The control valve sticks again when OP changes its direction at point E. Figure 1 explains the generic nature of sticky control valves. In practice, valves with stiction may function as explained above, but the amount of stiction (i.e., stiction band) may vary whenever stiction occurs.

4. PROPOSED METHOD

In this section, a comprehensive and thorough description of the proposed method is provided.

4.1. Stiction Detection.

The proposed method entirely depends on how PV responds to stiction in the control valve. Figure 2 displays oscillating PV and OP of the pressure control loop (CHEM 10) adopted from ISDB. The actual cause of oscillations in CHEM 10 is valve stiction. The trend of PV comprises two phases: transient and steady-state phases. When the valve is stuck, PV either remains constant or very slowly varies (small variations may be considered as noise) because process input (fluid flowing through the valve) stays unchanged. Once the valve overcomes stiction, it is able to move uninterruptedly until it becomes sticky again; therefore, the process input varies; as a result, the transient phase takes place. The valve may get stuck again and when it happens, the steady-state period occurs. After the valve has been released from stiction, the transient phase transpires. In the case of a healthy valve, as shown in Figure 3, both PV and OP contain solely one phase, i.e., transient phase. As the valve continuously moves, PV and OP change in the same direction or opposite direction. The main idea is to detect steady-state periods with the help of an OP signal. The key steps involved in the development of the proposed method are shown in Figure 4 and described in the following.

Step 1. PV, OP, and t (time) are split into a P number of nonoverlapping windows of width w (samples in one window do not present in another window).

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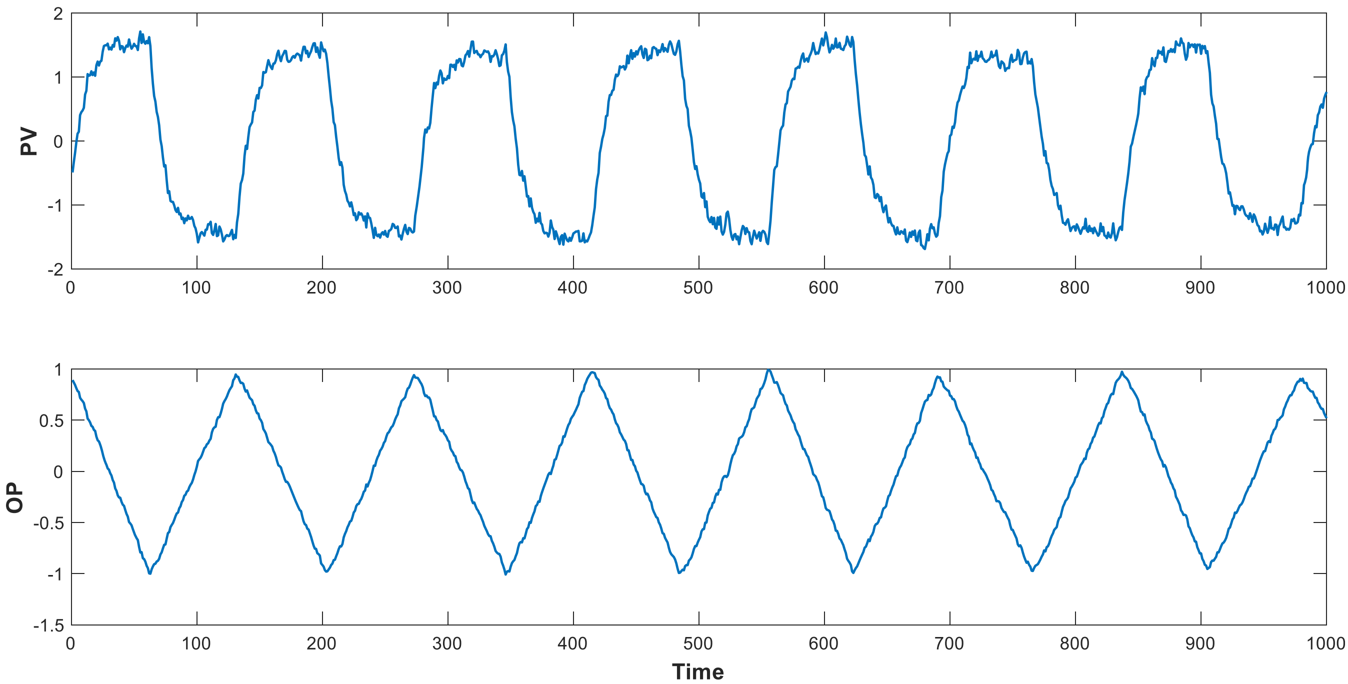

Figure 2. Pressure control loop with a sticky valve.[5]

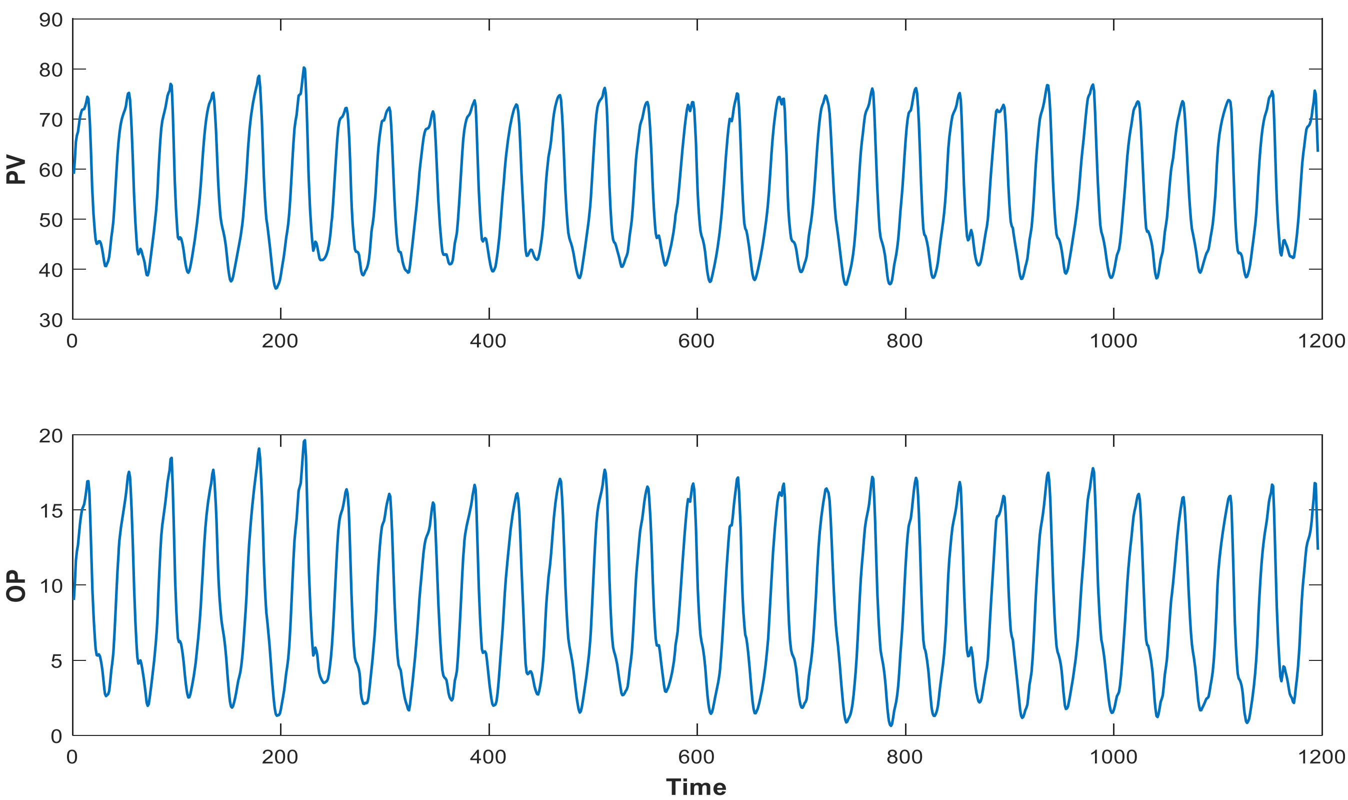

Figure 3. Concentration control loop (PAP 4) taken from ISDB.[5]

Step 2. In the ith window of the PV signal, a linear model (eq 1) is developed using the data available in that window.

$$y_j = m_i^{\mathrm{pv}} t_j + b_i^{\mathrm{pv}},\ j \in [(i-1) \times w,\ i \times w] \tag{1}$$

where j denotes the index of samples of PV, y_j and t_j are, respectively, the jth value of PV and t, and m_i^{pv} and b_i^{pv} are, respectively, the slope and intercept.

Similarly, a separate linear model is built in each of the remaining windows of PV. The same procedure is repeated for OP.

Step 3. If PV is slowly varying in the ith window, the slope (m_i^{pv}) of the linear model fitted to the corresponding data is close to 0 (or very small). In the same window of OP, the slope (m_i^{op}) of the respective linear model is far away from 0 since OP is constantly changing. Hence, the ratio ($m_i^{\mathrm{op}}/m_i^{\mathrm{pv}}$) is a

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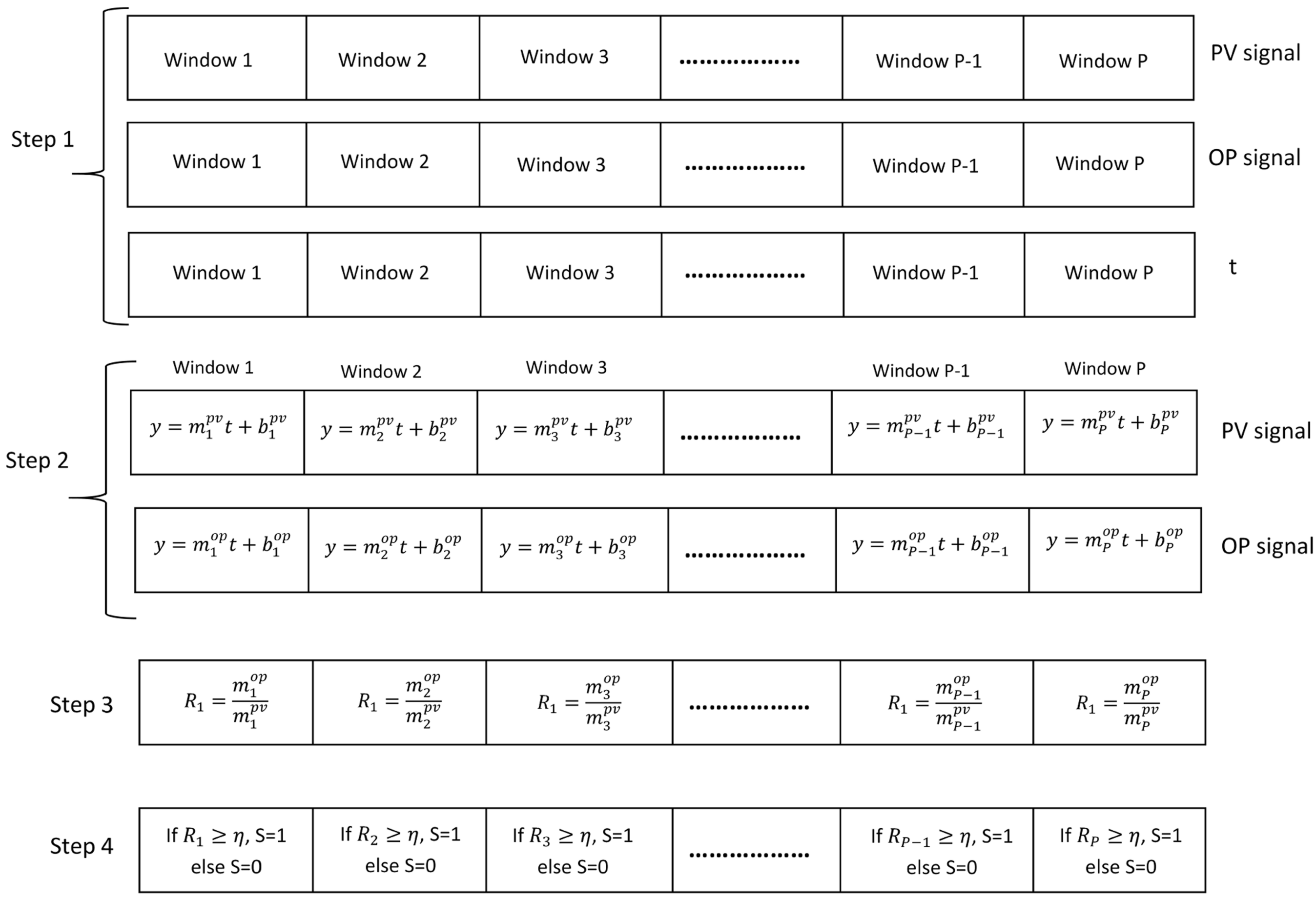

Figure 4. Visual interpretation of the proposed method.

large number that indicates the occurrence of valve stiction. Conversely, if PV is varying in the *i*th window, the ratio becomes small, which signifies the healthy state of the valve. Therefore, to detect steady and transient periods, the ratio of m_i^{op} and m_i^{pv} is computed.

Step 4. The ratios computed in step 3 are compared with the prespecified threshold η for determination of steady-state periods (or the incidence of valve stiction). If the ratio exceeds the threshold in any window, the stiction signal S becomes 1, otherwise zero. The stiction index given by the following equation is calculated.

$$\Phi = \frac{\sum_{i=1}^{P} S(i)}{P} \tag{2}$$

If none of the calculated ratios exceeds the threshold, then Φ = 0 and the valve is healthy. Pseudocode, which explains how to detect stiction in control loops using the proposed method, is provided in Section S1 in the Supporting Information file.

4.2. Stiction Quantification. Stiction can be quantified quite easily using the procedure explained as follows. The stiction signal S plays a decisive role in estimating the stiction band. The proposed method yields the stiction signal, as shown in Figure 5. The stiction signal S stays at 0 in windows 1−10, but in windows 11 and 12, S takes value of 1, i.e., the valve sticks in this period. The stiction band in windows 11 and 12 is estimated as

$$\xi_1 = |\mathrm{OP}((11 - 1) \times w + 1) - \mathrm{OP}(12 \times w)| \tag{3}$$

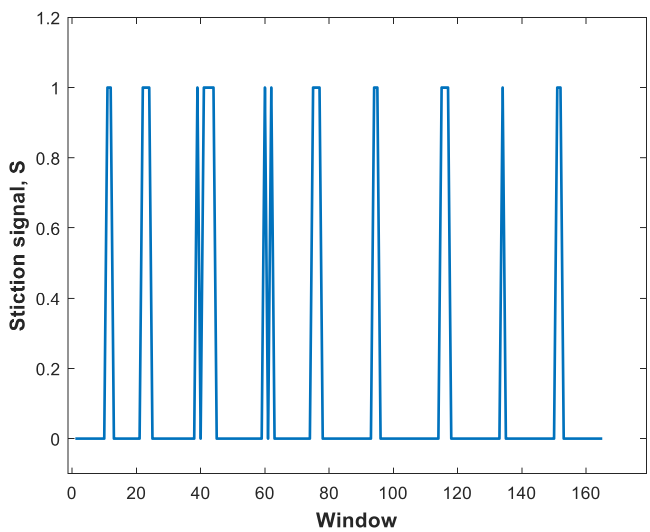

Figure 5. Stiction signal S.

The control valve sticks at the first sample of the 11th window and overcomes stiction at the $(12 \times w + 1)$th sample. The stiction signal immediately drops to 0 and remains at 0 in windows 13−21. The control valve again sticks in windows 22−24. Therefore, the stiction band in these windows is approximated as

$$\xi_2 = |\mathrm{OP}((22 - 1) \times w + 1) - \mathrm{OP}(24 \times w)| \tag{4}$$

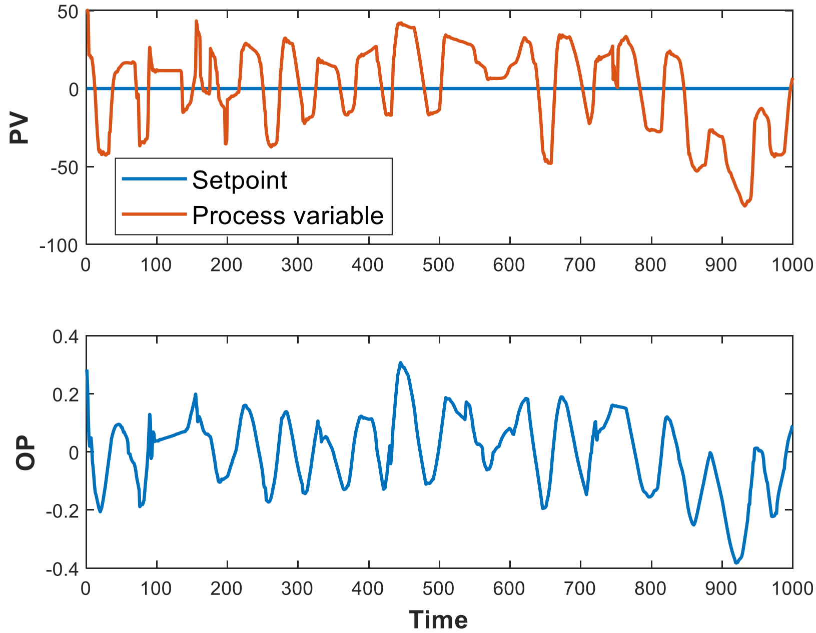

Figure 6. Closed-loop signals of CHEM 6.

If the stiction signal S becomes 1 in only one window, the absolute value of the difference between OP at the first sample of this window and OP at the last sample of the window is estimated as the stiction band. If the stiction signal S remains at one in more than one window (for example, windows 22–24), the value of OP at the first sample of the first window (i.e., window 22) is subtracted from the value of OP at the last sample of the last window (window 24), and the absolute value of the result is considered as estimation for the stiction band. In this fashion, the stiction band in the remaining windows can be approximated. The following expression provides the final estimation for the stiction band.

$$\Psi = \max\{\xi_j\}_{j=1}^{Q} \tag{5}$$

where Q is the number of windows in which S equals to 1.

Pseudocode for stiction quantification via the proposed method is provided in Section S2 in the Supporting Information.

4.3. Selection of Window Size (*w*) and Threshold (*η*). The performance of the proposed method exceedingly depends on the values chosen for w and η. In the case of a sticky valve with high stiction, PV experiences very small changes for a considerably long period of time. If a large value for w is used in this situation, it is less likely that the method produces false alarms. If the same w is employed in a valve with low stiction, the method will definitely fail to notice the event of stiction because the slowly varying behavior of PV lasts only for a short period of time. The same consequences may also be resulted if an inappropriate value is selected for the threshold. Therefore, the window size and the threshold need to be selected with great care.

5. RESULTS AND DISCUSSION

In this section, the applicability and effectiveness of the proposed method is examined by testing it in benchmark control loops along with control loops adopted from an oil sands industry

5.1. Selection of Optimum *w* and *η*. ISDB containing PV and OP of different control loops belonging to various industries, collected by Jelali and Huang,[5] provides benchmark control loops to assess the stiction detection capability of new methods. Among the available control loops in ISDB, the actual root causes of 20 oscillating control loops are known. These 20 control loops were adopted in the present work to validate the proposed method. To determine the best value for the window size and threshold of the proposed method, the proposed method was applied to the 20 control loops using different values of the window size and the threshold. The obtained results are provided in Tables S2–S9 and Figures S1–S5 (given in the Supporting Information file). The following observations were inferred from the results.

- When the window size is too small, control loops that are experiencing oscillations due to the nonstiction conditions will likely be misjudged by the proposed method. The oscillations caused by the nonstiction conditions are sinusoidal with smooth or sharp peaks (or valleys). In the case of smooth sinusoidal oscillations, data points near or at the peaks (or valleys) often stay close together. Therefore, the method will recognize data windows covering those data points as steady-state periods irrespective of the origin of the oscillations. That is why the method produced false alarms in the loops without stiction when small values of the window size were used.
- Small threshold also possesses the same outcome as the small window size. The slope ratio often becomes small in most data windows of the loops without stiction (such as CHEM 3, 13, 14, and 16 and PAP 2, 7, and 9) and disobeys the small threshold. Therefore, the method will misinterpret those data windows as the occurrences of valve stiction, which is evident from the results.
- Large window size leads to incorrect diagnosis in control valves with low stiction (CHEM 1, 6, 11, and 12, PAP 5, and MIN 1). For a short duration, the control valve in these loops does not move. As a result, PV experiences

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slight changes for that short duration. The valve overcomes stiction when enough driving force (OP) is received and moves continuously until sticks again. In this situation, large data windows also include data points (samples) belonging to the nonsteady state phase (i.e., moving phase of the valve) of the PV signal. For this reason, the slope ratio becomes small and always stays below the threshold. As a result, the control valve in the control loops will be falsely judged as healthy. Similar behavior of the method can be noticed when a large threshold was employed.

- As far as CPU usage is concerned, overall stiction detection time (time taken to diagnose the 20 loops) increases with decreasing window size.
- Based on the results and the above discussion, the optimum values of w and η can be determined as 6 and 15, respectively, which can ensure that valves with varied degrees of stiction (low, medium, and high) can be detected.

5.2. Detection of Sticky Valves. *5.2.1. Benchmark Control Loops.* For all of the control loops studied in this work, fixed window size (w = 6) and threshold (η = 15) are employed. As the data are attained from real industries, the data may be corrupted by noise; hence, the closed-loop signals of the control loops were denoised using wavelets.

Figure 6 displays the closed-loop signals of the flow control loop (CHEM 6) with a sticky control valve. It is hard to find a perfect square shape or triangle shape in PV or OP, respectively. Further, the phase plot shown in Figure 7 is

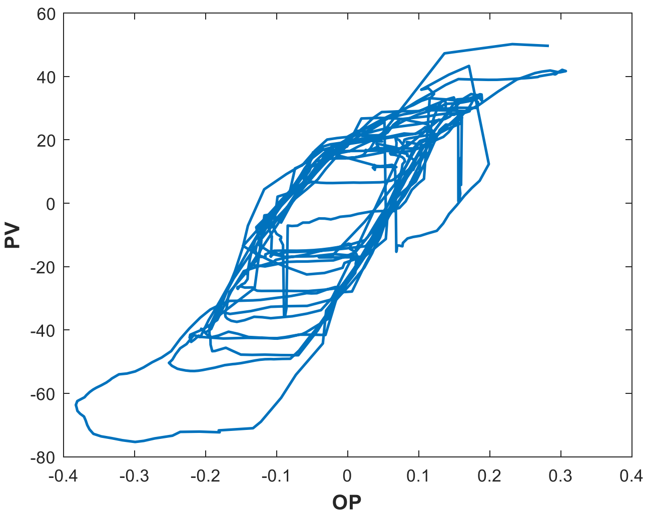

Figure 7. Phase plot of CHEM 6.

neither an ellipse nor a parallelogram. Hence, waveform or limit cycle patterns-based methods cannot detect stiction in CHEM 6. The proposed method was applied to CHEM 6, and the obtained results are presented in Figures 8 and 9, and Table 2. It is observed from Figure 8 that the slope ratio R violated the threshold η in 16 out of 165 windows. Based on the calculated stiction index Φ and the obtained estimation for the stiction band, the proposed method confirmed the presence of mild stiction in the control valve in CHEM 6. Table 2 provides the verdicts issued by the proposed method for the 20 control loops. The qualitative results of representative control loops are shown in Figures 10−13. The values of Φ and Ψ obtained for PAPA 7 suggest that the

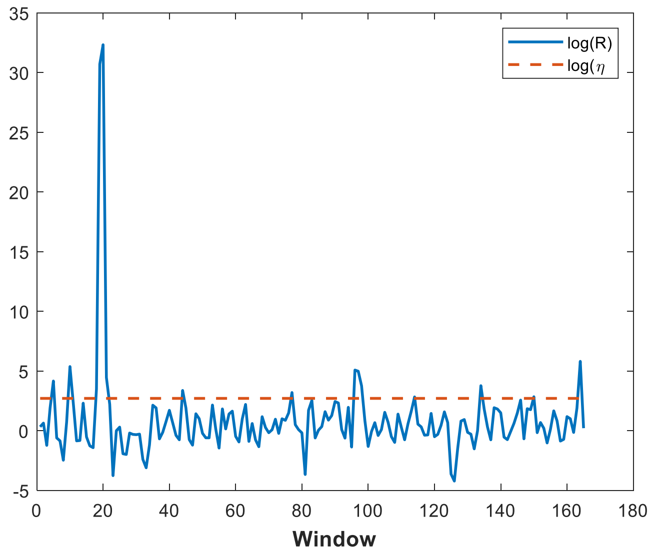

Figure 8. Slope ratio obtained in each window (CHEM 6).

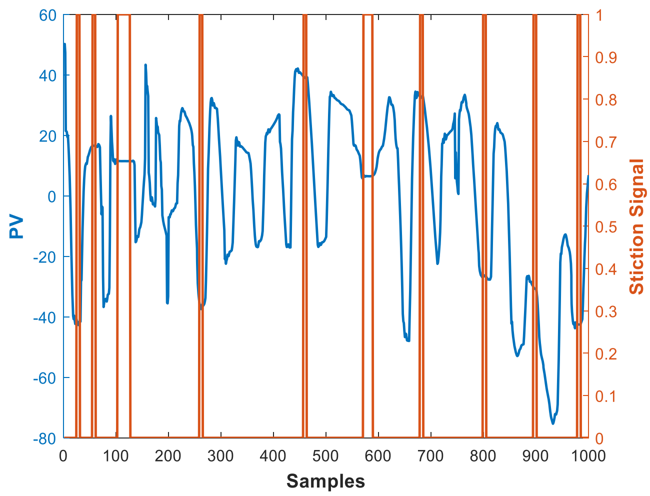

Figure 9. Results for CHEM 6.

control valve in this control loop is healthy and some nonstiction conditions could have induced the oscillations. Therefore, the verdict for PAP 7 was considered as nonstiction. The proposed method provided a correct diagnosis in 17 out of the 20 control loops. To know if the proposed method can compete with methods reported in literature for stiction detection, the performance of the proposed method is compared with that of the existing methods reported in Table 1. The proposed method delivered the same performance as BSD but outpaced the remaining methods. The advantage of the proposed method over the BSD method will be demonstrated next.

5.2.2. Oil Sands Control Loops. To know whether the proposed method and the BSD method[12] work beyond the benchmark control loops, flow (Figure 14), temperature (Figure 15), and pressure (Figure 16), control loops from an oil sands industry are considered in this section.

All of the control loops manifest oscillations. To protect process information, the signals PV and OP were normalized to [0, 100%] from their real ranges. Control engineers from the oil sands industry confirmed that valve stiction is the real reason for the undesirable performance of the control loops.

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Table 2. Results of the Proposed Method

loop name	actual malfunction	stiction index, Φ	correct diagnosis?	estimated stiction band, Ψ (%)
CHEM 1	stiction	5.5762	yes	0.1278
CHEM 2	stiction	13.9394	yes	3.6431
CHEM 3	nonstiction	21.0526	no	1.01
CHEM 6	stiction	9.0909	yes	0.1017
CHEM 10	stiction	9.6970	yes	0.3112
CHEM 11	stiction	4.2424	yes	0.2846
CHEM 12	stiction	2.7108	yes	0.1228
CHEM 13	nonstiction	0	yes	0
CHEM 14	nonstiction	10.4418	no	2.3766
CHEM 16	nonstiction	2.8112	no	1.2086
CHEM 23	stiction	20.0803	yes	13.5556
CHEM 24	stiction	27.3092	yes	18.3958
CHEM 29	stiction	6.8390	yes	8.9380
CHEM 32	stiction	12.6506	yes	10.9320
PAP 2	stiction	2.5253	yes	1.9587
PAP 4	nonstiction	0	yes	0
PAP 5	stiction	4.8016	yes	0.1606
PAP 7	nonstiction	0.5960	yes	0.0948
PAP 9	nonstiction	0	yes	0
MIN 1	stiction	5.6948	yes	0.2166

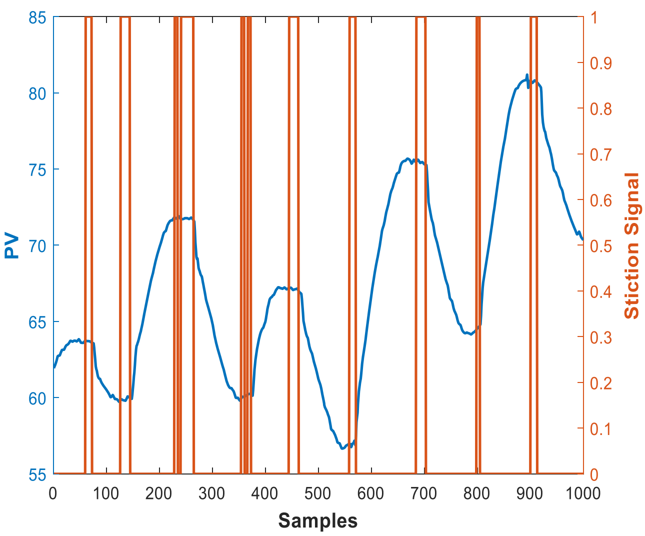

Figure 10. Results for CHEM 2.

The results of the proposed method are shown in Figures 17−19 and Table 3. The BSD method relies on butterfly shape that appears in phase plot drawn using modified OP and PV data. In line with Figures 20−22, the BSD method identified stiction in the pressure control loop but failed in the flow and temperature control loops as the shape in Figures 20 and 21 are not a perfect butterfly. Contrariwise, the proposed method successfully recognized stiction in both the control loops (Figure 22).

5.3. Detection of a Faulty Valve. Consider a steam flow control loop taken from the same oil sands industry adopted in Section 5.2.2. The PV and OP signals of the steam flow control loop are displayed in Figure 23. The steam combines with the treated feed gas, upstream of a packed bed reactor, in a mixed tee to form a mixed stream. From Figure 23, it is noticed that PV follows SP until the 53rd sample, and then both PV and SP change in the opposite direction for some time due to process disturbances. At around the 54th sample, the steam controller

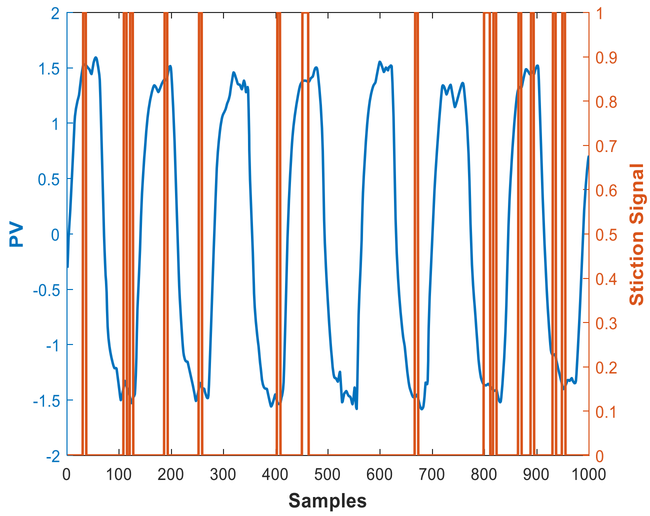

Figure 11. Results for CHEM 10.

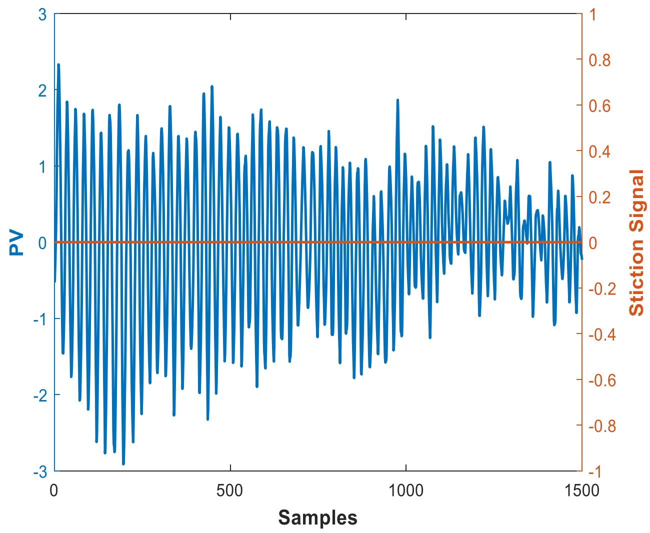

Figure 12. Results for CHEM 13.

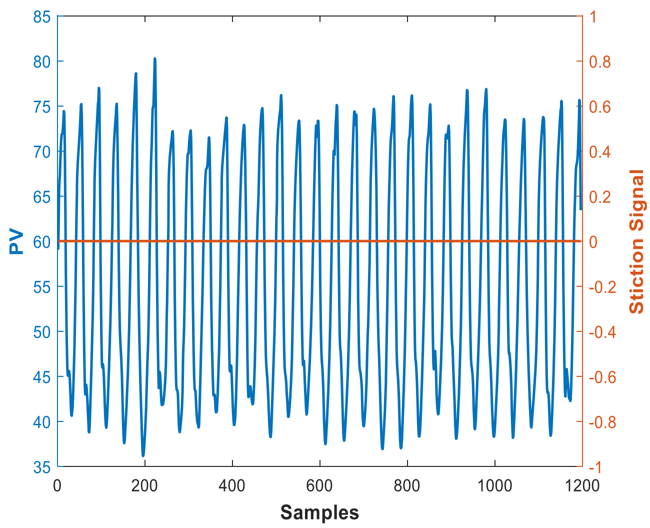

Figure 13. Results for PAP 4.

starts closing the steam control valve slowly; as a result, OP keeps decreasing, but PV did not follow the OP change due to

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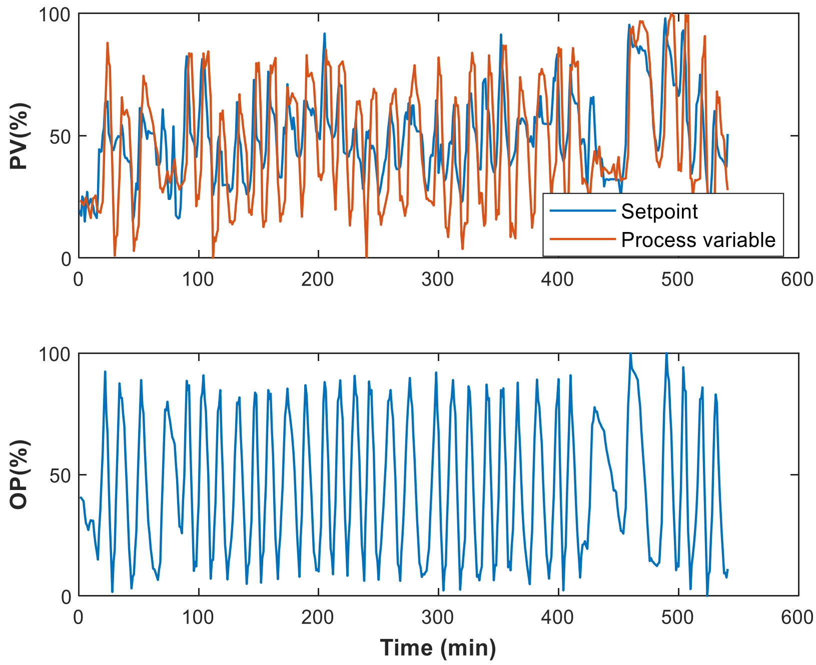

Figure 14. OP and PV signals of a flow control loop from the oil sands industry.[10]

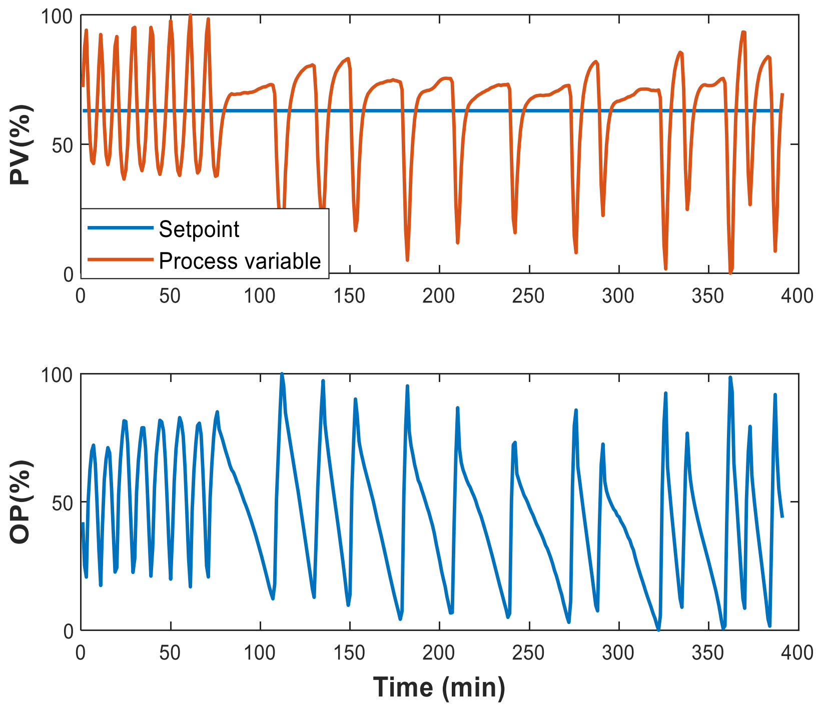

Figure 15. OP and PV signals of a temperature control loop from the oil sands industry.[10]

severe valve stiction. When OP dropped large enough, it caused sudden movement in the steam valve, and thus steam flow was reduced to below its trip setpoint, which resulted in plant trip. As per the results shown in Figure 24, the proposed method identified and quantified severe valve stiction in the flow control loop. The flow control loop owns both steady-state (prior to valve closure) and dynamic characteristics (after valve closure). After severe stiction had taken place, PV and OP did not show cycling behavior. Because of the absence of sustained oscillations in PV and/or OP, the existing method, BSD, could not detect severe stiction (Figure 25).

The results shown in Figures 20, 21, and 25 unveil that the performance of the BSD method[12] is likely to be influenced by the presence of noise in PV and/or OP and concurrent occurring of stiction and one or more of the nonstiction conditions. In addition, as noticed in Figure 23, valves with severe stiction, which cause a plant to trip, exhibit static behavior followed by transient behavior. When such event occurs, a complete limit cycle is hard to find. The BSD method may not be useful to detect sudden valve closures or valves with severe stiction. In view of the above discussion, the proposed method has additional benefits of being able to work

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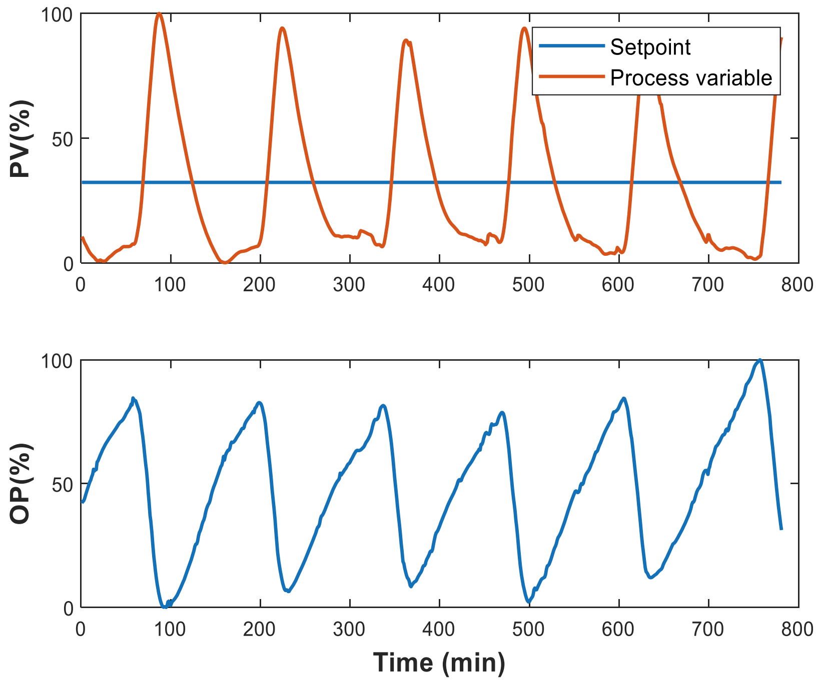

Figure 16. OP and PV signals of a pressure control loop from the oil sands industry.[10]

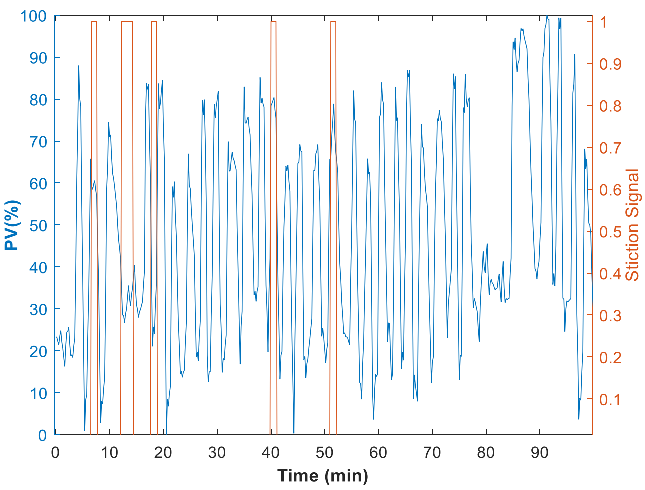

Figure 17. Stiction detection in a flow control loop.

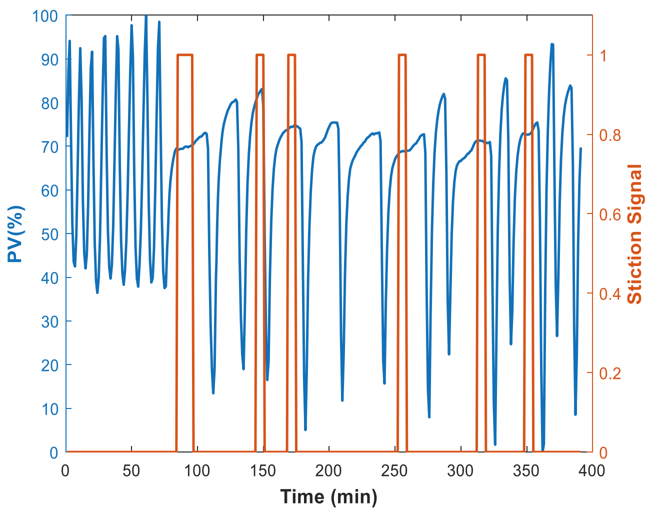

Figure 18. Stiction detection in a temperature control loop.

further than the benchmark loops and recognize abrupt valve closure.

5.4. Effect of Noise. The closed-loop signals of the benchmark control loops taken from ISDB are originally noisy, so they were only considered to study the effect of noise on the performance of the proposed method.

The proposed method was applied to the raw closed-loop signals (noisy signals not preprocessed). The results are provided in Table S10 given in the Supporting Information file. In the presence of noise, the proposed method issued correct verdicts in 16 out of the 20 control loops. Even though control valve in PAP 4 is healthy, due to noise, the method falsely detected the presence of stiction. The method quantified the amount of stiction in CHEM 1 and CHEM 12 to be 0.063 and 0.048%, respectively, which are smaller than those given in Table 2 (results belong to noise-free signals). In each of the remaining loops, the stiction band approximated from the noisy signals (Table S10) is, to a moderate extent, close to the stiction band estimated from the noise-free signals (Table 2). This shows that the noise had a small impact on the stiction detection and quantification capabilities of the proposed method.

In the absence of noise, during valve stiction, PV intermittently reaches steady state while OP is continuously changing. So strict steady-state periods appear in PV. In practice, sensor readings are often associated with noise, pseudo-steady-state periods can only come into sight in PV as shown in Figure 2. Instead of staying at a constant value, PV oscillates due to noise. The proposed method looks for pseudo-steady-state periods by fitting a linear regression model to data present in each window. If the noise is low (as per Figure S6 provided in the Supporting Information file), in each of the windows, the slope of the linear model is not exactly 0 but relatively small. When the slope of the linear model fitted to OP data in a window is divided by the slope of PV data in

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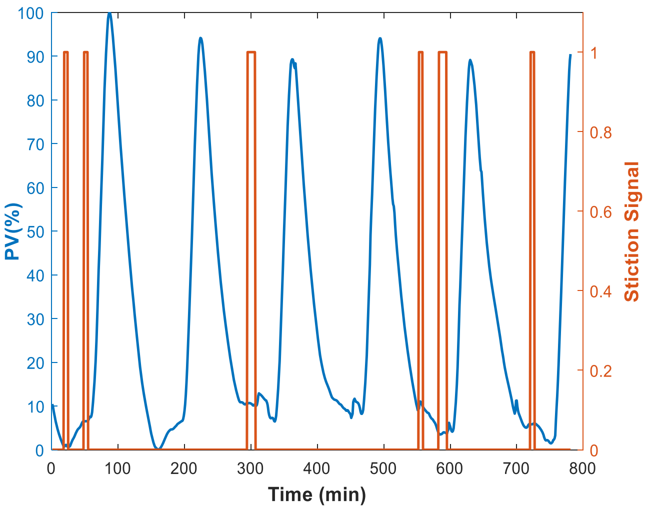

Figure 19. Stiction detection in a pressure control loop.

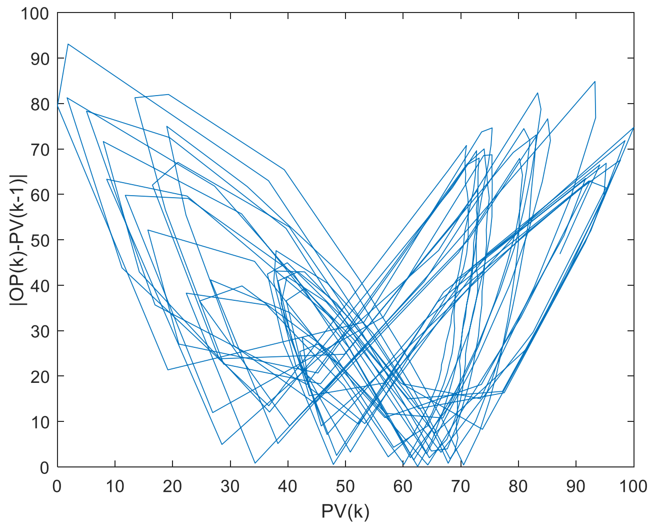

Figure 21. BSD plot for a temperature loop.

Table 3. Results for Oil Sands Control Loops

control loop	actual malfunction	stiction index, Φ	correct diagnosis?	estimated stiction band, Ψ (%)
flow	stiction	6.7416	yes	3.3860
temperature	stiction	10.9375	yes	8.3244
pressure	stiction	6.2016	yes	0.7065

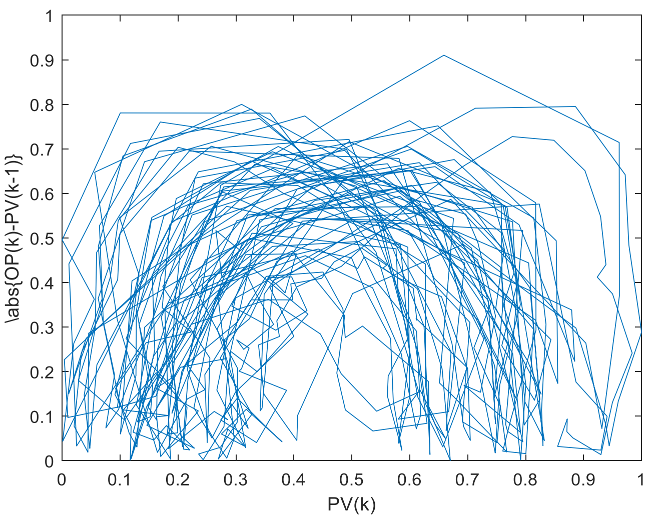

Figure 20. BSD plot for a flow control loop.

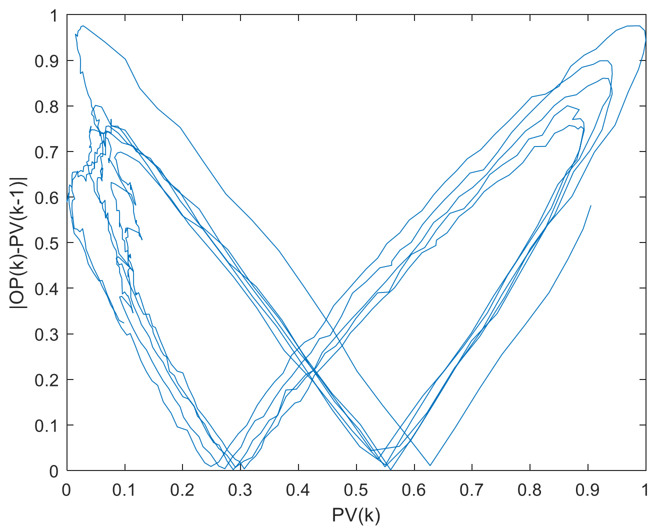

Figure 22. BSD plot for a pressure control loop.

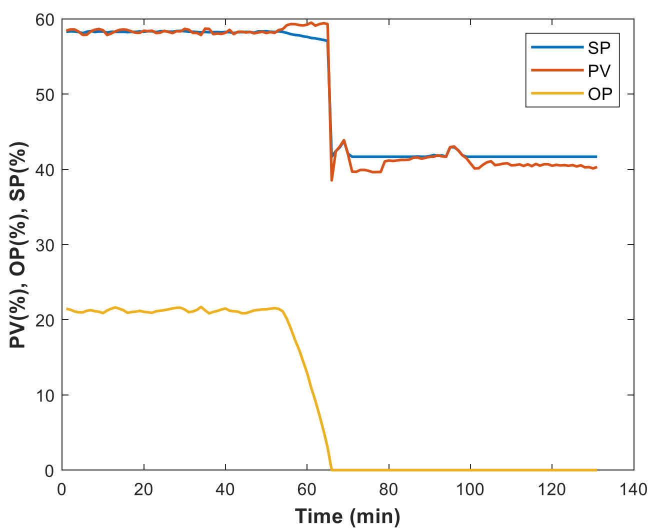

Figure 23. Steam flow control loop with a faulty valve.[10]

the same window, this ratio becomes moderately large and exceeds the given threshold. In this situation, the method identifies most of the pseudo-steady-state periods (i.e., occurrences of stiction). On the other hand, if the noise in PV is high (Figure S7 given in the Supporting Information file), PV oscillates with a larger amplitude and higher frequency. The proposed method detects some of the pseudo-steady-state periods and hence identifies the presence of stiction in the control loop. This way, the method tries to identify stiction from noise.

Considering the above discussion, it can be said that the proposed method demonstrated a noteworthy degree of robustness to the noise in closed-loop signals.

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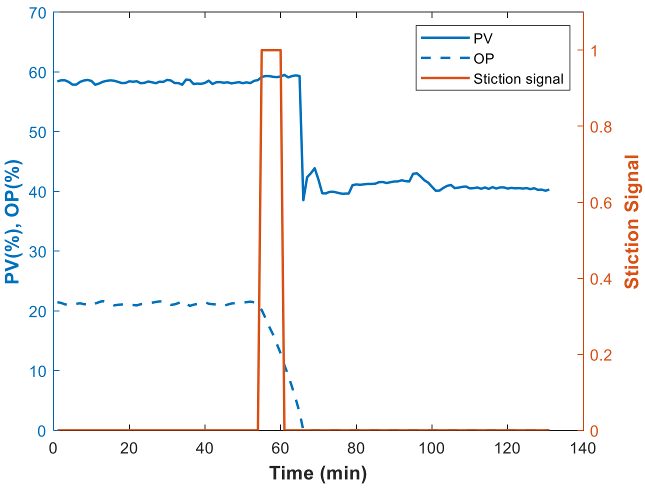

Figure 24. Results of the proposed method. The stiction index and stiction band were determined to be 5 and 7.2486.

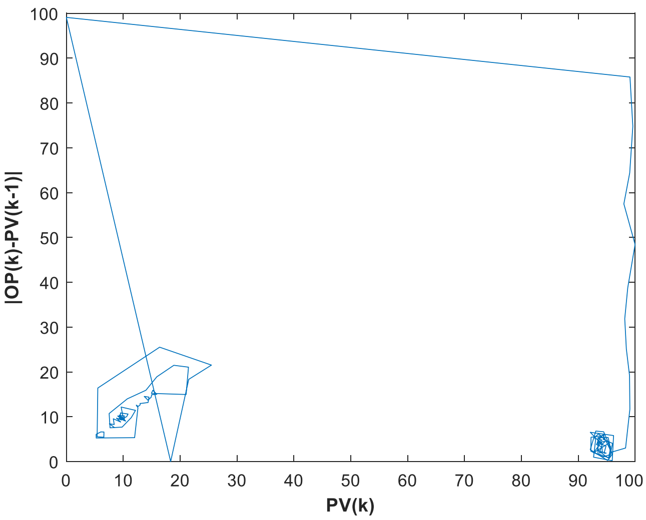

Figure 25. BSD plot for the steam flow control loop.

5.5. Advantages of the Proposed Method over the Existing Methods.

The following demonstrates the superiority of the proposed method over the existing methods.

- The proposed method has been founded on the response of a control loop to a sticky control valve, i.e., slowly varying nature of PV during valve stiction. Because of this trait, the method can detect stiction (as observed in Sections 5.2.1, 5.2.2, and 5.3) even though the waveform shapes (square, triangular, or sinusoidal waves), limit cycle patterns (ellipse or parallelogram), and butterfly shape do not appear in a PV, OP, or phase plot (PV vs OP).
- The theory of the proposed method is simple to understand by any user who has basic knowledge in statistics and linear regression. According to the pseudocodes given in Sections S1 and S2 in the Supporting Information, the method requires a few lines of control language code to be implemented in the distributed control system (industrial settings). The method needs little computational power and produces results very quickly. These attributes make the method highly suitable for industries.
- In addition to detecting and estimating stiction, the method can recognize faulty valves (valves with severe stiction or sudden valve closures), which is a great benefit over the existing methods.
- The method is equally applicable to stationary and nonstationary signals, and signals with multiple oscillations.
- The method can identify valves with varying degree of stiction.
- The results shown in Sections 5.2 and 5.3 prove that the method can compete with all of the existing methods.

6. CONCLUSIONS

The present work introduced a new and simple methodology to detect sticky control valves in industrial control loops. The merit of the proposed method was illustrated through application in industrial case studies comprising benchmark control loops and control loops from the oil sands industry. The proposed method showed an 85% success rate in the benchmark control loops, which most of the existing methods could not reach, and provided a correct diagnosis in all of the oil sands control loops containing sticky and faulty control valves.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.iecr.1c02723.

Full forms for acronyms used in Table 1, pseudocode to detect stiction via the proposed method, pseudocode to quantify stiction via the proposed method, stiction index for various values of window size and threshold, stiction detection time for different values of window size and threshold, and results for raw closed-loop signals of the benchmark control loops (PDF)

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Notes

The authors declare no competing financial interest.

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