A SIMPLE TEST TO CONFIRM CONTROL VALVE STICTION

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Abstract: Stiction is a common problem in the widely used spring-diaphragm type control valves in the process industry. Several methods are available for detecting stiction in control valves. After detection of stiction, a test is required to confirm that the valve in question is indeed suffering from stiction. This paper presents a simple closed loop test, based on changing only the controller gain, for confirming the presence of stiction. The method does not require that the loop be put in manual, which can otherwise upset the plant. The usefulness of this test is demonstrated through simulation studies and an industrial application.

Keywords: Control loops, Control valves, Dead band, Process control, Nonlinearity, Static friction.

1. INTRODUCTION

A typical chemical plant has hundreds of control loops. The presence of oscillation in a control loop increases the variability of the process variables thus causing inferior quality products, larger rejection rates, increased energy consumption, reduced average throughput and profitability. Bialkowski (1992) reported that about 30% of the loops are oscillatory due to control valve problems. In a recent industrial survey, Desborough and Miller (2002) found that control valve problems account for about a third of the 32% of controllers classified as "poor" or "fair". Among the many types of nonlinearities in control valves, *e.g.* stiction, backlash and dead band, stiction is one of the most common and long-standing problems in process industries.

Stiction can easily be detected using invasive methods such as the valve travel or bump test. However, it is neither feasible nor effective to apply an invasive method across an entire plant site due to the requirement of significant manpower, cost and time. Although many studies (Taha *et al.*, 1996; Wallén, 1997; Sharif and Grosvenor, 1998; Gerry and Ruel, 2001) have been carried out for invasive analysis of control valve performance, only a few non-invasive methods (Horch, 1999; Rengaswamy *et al.*, 2001; Stenman *et al.*, 2003; Choudhury *et al.*, 2004*c*) have appeared in the literature.

These non-invasive methods are capable of detecting stiction in control valves. But all of these methods work with single loops and do not take into account the propagation of oscillation. Stiction in one control

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valve may generate limit cycle oscillations that can easily propagate to other loops of the connected adjacent units. That is why all the noninvasive methods when applied to an entire plant site may detect stiction in a large number of control valves. This necessitates the need of a plant test to confirm and isolate the valves which are indeed suffering from stiction.

A common industrial practice to confirm stiction is to put the loop in manual and observe the behavior of the oscillatory loop. If the limit cycle of the oscillation dies out, the valve is confirmed to be sticky. In many cases, it is not possible to put the loop in manual due to various reasons including safety, disruption in plant production and undesirable effect on other loops. Therefore, a test that does not require putting the loop in manual and can be applied online while the loop is still closed, is invaluable for the process industries. This study describes such a simple test to confirm stiction in control valves.

2. WHAT IS STICTION?

Different people or organizations have defined stiction in different ways. A review of these available definitions is available in (Choudhury *et al.*, 2004*a*). Based on a careful investigation of real process data, Choudhury *et al.* (2004*a*) also proposed a new definition of stiction, which is summarized as follows:

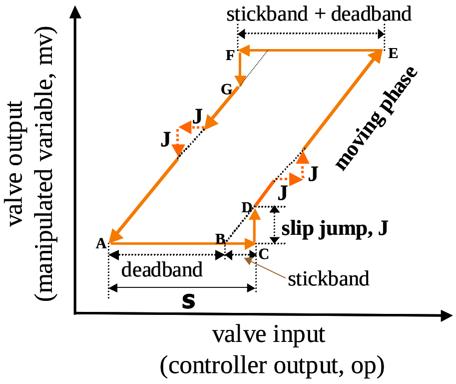

Fig. 1. *Typical input-output behavior of a sticky valve*

The phase plot of the input-output behavior of a valve “suffering from stiction” can be described by Figure 1. It consists of four components: dead band, stickband, slip jump and the moving phase. When the valve comes to rest or changes the direction at point A in Figure 1, the valve sticks. After the controller output overcomes the dead band (AB) plus the stickband (BC) of the valve, the valve jumps to a new position (point D) and continues to move. Due to nearly zero velocity, the valve may stick again in between points D and E in Figure 1, while travelling in the same direction (EnTech, 1998). In such a case the magnitude of dead band is zero and only stickband is present. This can be overcome if the controller output signal is larger than the stickband only. Once the valve slips, it continues to move until it sticks again (point E in Figure 1). Formally stating,

Definition 1. Stiction is a property of an element such that its smooth movement in response to a varying input is preceded by a static part followed by a sudden abrupt jump called the slip jump. In a mechanical system, the slip jump originates due to static friction, which exceeds the dynamic friction during smooth movement.

3. METHODS TO CONFIRM VALVE STICTION

Due to the shortcomings of the stiction detection methods discussed in the section 1, usually a plant test is required to confirm if the suspected valves are indeed suffering from stiction. The various methods for confirming valve stiction are as follows:

(1) **Valve Travel or Bump Test:** Stiction in control valves is usually confirmed by putting the valve in manual and increasing the control signal in small increments until there is an observable change in the process output. This test is known as the valve travel or bump test (Taha *et al.*, 1996; Wallén, 1997; Gerry and Ruel, 2001). This method of confirming stiction by putting the loop in manual is not convenient and cost-effective due to the risk of plant upset and production of more ‘off-spec’ products.

(2) **Use of Valve Positioner Data:** For smart valves, usually the valve positioner (actual stem position of the valve) data is available. If the plot of valve positioner (mv) data against the valve input (op) data shows a pattern similar to that described in Figure 1, it can be concluded that this valve has stiction. Unfortunately, most industrial valves (more than 95% cases) are not smart valves because of the high initial and maintenance costs. The lack of availability of the valve positioner data restricts the application of this simple test to only a few cases.

(3) **Changes in Controller Gain:** This study describes a simple alternative test that can be applied online without affecting the plant production significantly. Presence of stiction in a control loop produces limit cycle oscillations in the process output (pv) and the controller output(op). Changes in controller gain cause changes in amplitude and frequency of these limit cycle oscillations. Once stiction is detected in a loop, changes in oscillation frequency due to variation in controller gain can help confirm the presence of stiction in the loop.

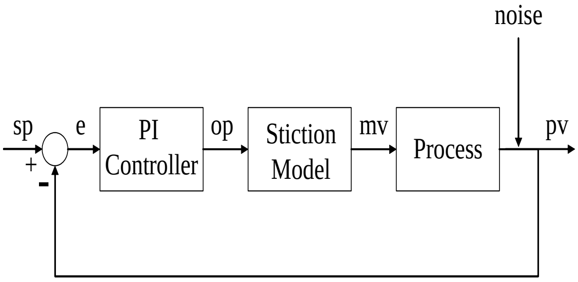

Fig. 2. *Block diagram of a simple SISO process with stiction nonlinearity in the valve*

4. SIMULATION STUDY

In this section, the effect of changing controller gain on the behavior of a control loop with sticky valve is shown through simulation examples. Figure 2 shows the block diagram of the simulation study. The PI controller is implemented in the form of the following equation:

$$C(s) = Kc\left(1 + \frac{1}{\tau_i\, s}\right) \tag{1}$$

A two parameter stiction model developed by (Choudhury *et al.*, 2004*a*; Choudhury *et al.*, 2004*b*) was used to introduce the stiction behavior of the control valve in the closed loop process. Two parameter are deadband plus stickband (S) and slip jump (J)(see figure 1). A 3% stiction ('S') with 1% slip jump ('J') were used in all simulations.

Simulation results are shown in figure 3. For all cases, the limit cycles were present even though the set point to the loop was zero. That is, they were internally generated and sustained by the loop in the absence of any external setpoint excitation.

4.1 A concentration control loop with a sticky valve

The transfer function model for this loop was obtained from (Horch and Isaksson, 1998). The process describes mixing of pulp and water to attain a desired concentration of pulp at the outlet. The transfer function model describes the dynamics of mixing pulp with water from the inlet of the water flow control valve to the outlet of the mixing chamber. The transfer function for the process ($G(s)$) has been given by:

$$G(s) = \frac{3e^{-10s}}{10s + 1} \tag{2}$$

The first panel of Figure 3 shows the limit cycles induced in this control loop by the sticky valve. After the first 400 samples, the controller gain, K_c, was doubled and it was again multiplied by two after 800 samples. Please note that for all cases data representing transient behavior right after the change of controller gain has been removed and the steady limit cycle oscillations are presented in order to better visualization of the change of frequency of the limit cycle oscillations. The top plot clearly shows that with the increase of the gain, both the amplitude and frequency of the limit cycle oscillation have increased.

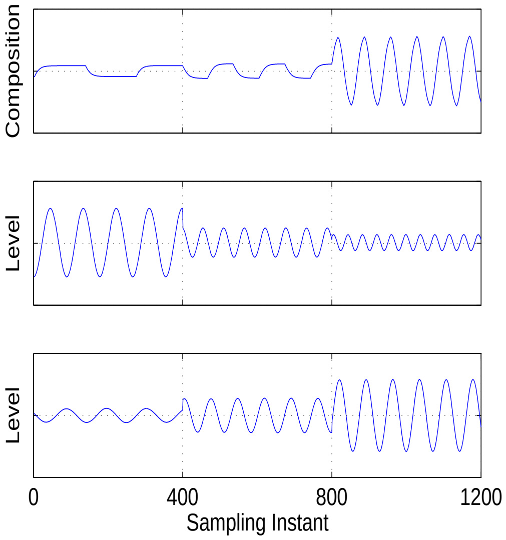

Fig. 3. *Effect of changing controller gains on the limit cycles generated by a sticky valve. The top plot corresponds to the concentration loop, the middle plot for the level loop, and the bottom plot for the composite concentration and level loop. Controller gains were doubled after each 400 samples.*

4.2 A level control loop with a sticky valve

The transfer function for this level loop was a pure integrator in the form of $\frac{1}{s}$. The middle plot of Figure 3 shows the result of increasing controller, K_c, gain. Again, the gain of the controller was doubled after 400 samples and it was again doubled after 800 samples. This plot also shows that an increase in controller gain for level loop increases the frequency of oscillation but reduces the amplitude of oscillation.

4.3 Connected concentration and level control loops

This case demonstrates propagation of oscillation(s) from one loop to another. This simulation case has been formulated by feeding the output of the concentration loop as disturbance to the level control loop. The stiction block from the level control loop was removed. In reality, it may describe a scenario where the outlet of a mixing chamber in a composition loop is used to feed another processing unit, e.g., a stock tank, and the level of the tank is controlled by another PI controller. The level of the tank may oscillate due to the presence of stiction in the concentration loop control valve. This oscillation can be considered as an external oscillatory disturbance to the level loop. All stiction detection algorithms (Horch, 1999; Rengaswamy *et al.*, 2001; Stenman *et al.*, 2003; Choudhury *et al.*, 2004*c*) will detect stiction in both loops because all of the algorithms work only on the assumption of single loop basis and do not consider the interaction among the loops, especially this kind of propagated oscillation. Now to differentiate between the loops suffering from stiction and the loops oscillating due to propagated oscillatory disturbances, the proposed method of controller gain change can be applied.

The results for this composite loop are shown in the bottom row of Figure 3. This describes how the level changes with the changes of the gain of concentration loop controller and level loop controller. After 400 samples, the gain of the concentration loop controller was doubled. This increases the frequency of the oscillation generated in the concentration loop, which in turn increases the frequency of oscillation in the level control loop. After 800 samples, the gain of the level controller was doubled, but the frequency of oscillation in the level has not increased rather it remained constant. This confirms that this is an external oscillatory disturbance and not generated within the loop. So, the level control valve is not suffering from stiction.

4.4 *Conclusion from the simulation study*

The following conclusions can be drawn from the simulation study:

- If a limit cycle oscillation is generated internally within a loop due to valve stiction, an increase in controller gain will increase the frequency of oscillation.
- If a limit oscillation enters in a loop as an external disturbance, a change in controller gain will not change the frequency of oscillation.
- There is no consistency in the change of the amplitude of limit cycle oscillations with the change of controller gain.

5. DESCRIBING FUNCTION ANALYSIS

In this section, describing function analysis is used to provide a justification for the observed closed loop behavior due to changes in controller gain.

A non-linear actuator with a stiction characteristic may cause limit cycling in a control loop. Further insights into the behavior of such systems may be achieved through a describing function analysis (Cook, 1986). The non-linearity is modelled by a non-linear gain N. The inherent assumptions of this approximation are that there are periodic signals present in the system and that the controlled system acts as a low pass filter and responds principally to the fundamental Fourier component. The condition for oscillations in a negative feedback loop is that the loop gain be -1 or:

$$L_o\left(i\omega\right) = -\frac{1}{N\left(X_m\right)} \qquad (3)$$

where $L_o\left(i\omega\right) = G\left(i\omega\right)C\left(i\omega\right)$ is the loop gain evaluated at frequency ω, and $N\left(X_m\right)$ is the describing function which depends on the magnitude of the controller output X_m. When condition (3) is met, the system will spontaneously oscillate with a limit cycle. The variation of the quantity $-1\,/N(X_m)$ with signal amplitude implies that signals initially present in the loop, *e.g.* noise, can grow until they are big enough to satisfy the equality and hence provide a self-starting oscillation. The solution to the complex equation $L_o(i\omega) = -1\,/N(X_m)$, if one exists, may be found graphically by superimposing plots of $L_o\left(i\omega\right)$ and $-1/N$ on the same set of axes.

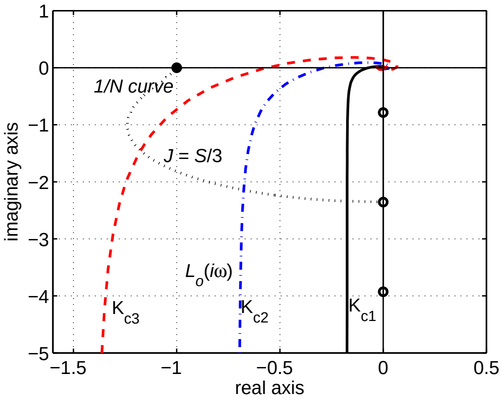

Fig. 4. *Graphical solutions for limit cycle oscillations in the concentration control loop. Dotted line is the* $-1/N$ *curve. The solid line, the dash-dotted line and the dashed line are for the frequency response function of the overall process,* $L_o(i\omega)$*, where* $K_{c1} < K_{c2} < K_{c3}$.

5.1 *Expression for describing function*

The describing function of a non-linearity is given as:

$$N = \frac{Y_f}{X} \qquad (4)$$

where X is a harmonic input to the non-linearity having angular frequency ω_o and Y_f is the fundamental Fourier component with angular frequency ω_o of the output from the non-linearity. As shown in (Choudhury *et al.*, 2004*b*) the describing function for the two parameter stiction model can be represented as:

$$N = -\frac{1}{\pi X_m}\left(A - iB\right) \qquad (5)$$

where,

$$A = \frac{X_m}{2}\sin 2\phi - 2X_m\cos\phi - X_m\left(\frac{\pi}{2} + \phi\right) + 2\left(S - J\right)\cos\phi \qquad (6)$$

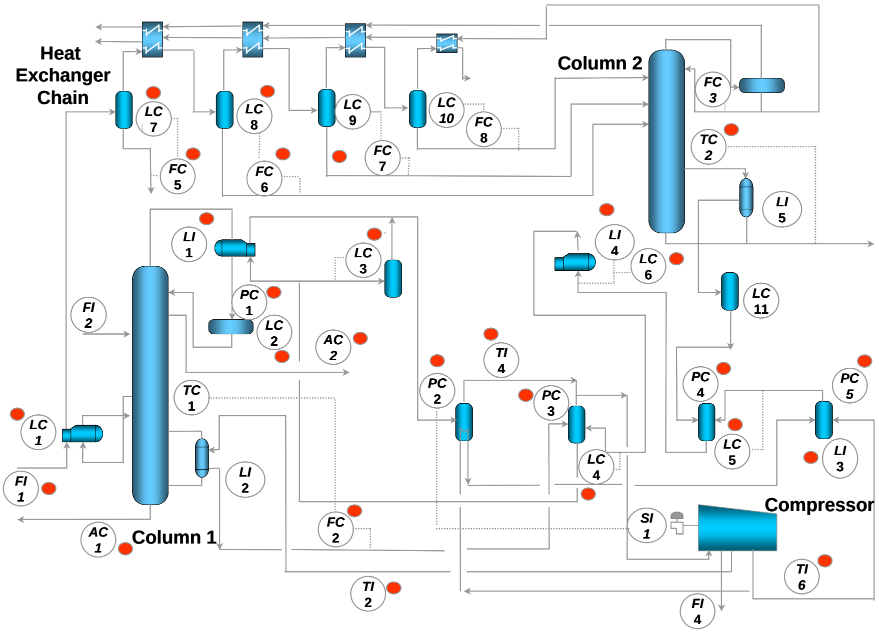

Fig. 5. *Process flow diagram for the industrial process showing the variables oscillating with same time period as condenser level ($LI1$). The plant-wide nature of the oscillations should be noted.*

$$B = -3\frac{X_m}{2} + \frac{X_m}{2}\cos 2\phi + 2X_m \sin\phi - 2\left(S - J\right)\sin\phi \quad (7)$$

$$\phi = \sin^{-1}\left(\frac{X_m - S}{X_m}\right) \quad (8)$$

5.2 *Describing function analysis of the concentration loop*

Figure 4 shows the graphical solutions of the equation (3) for the composition control loop. The system is closed loop stable and thus both the curves, $L_o(i\omega)$ and $1/N(X_m)$, intersect the negative real axis between 0 and -1.

It is clear from Figure 4 that there will be a limit cycle for the composition control loop because of the intersection of the $1/N(X_m)$ curve and $L_o(i\omega)$ curve. With the increase of controller gain, K_c, the intersection point moves to a higher frequency. Thus, the describing function analysis correctly predicts that an increase in controller gain will increase the frequency of limit cycle oscillation.

6. INDUSTRIAL APPLICATION

The need for the method for confirming valve stiction, as presented in this paper, was motivated by an industrial case study. The plant personnel at Mitsubishi Chemical Corporation, Mizushima, Japan reported oscillations with large amplitude in the condenser level of a distillation column causing sub-optimal operation and large economic losses. Previous attempts for oscillation diagnosis by considering only the level and the variables directly affecting them were not successful.

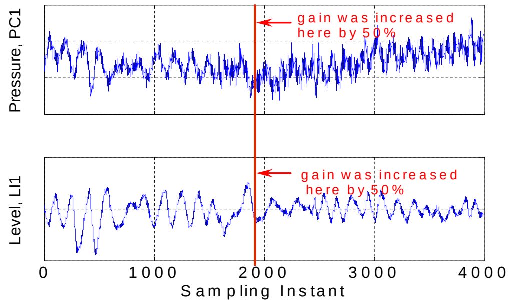

Fig. 6. *Effect of changes in controller gain on the oscillatory behavior for the industrial process. The first and second plots correspond to the variables $PC1$ and $LI1$ respectively.*

Before a full scale diagnosis exercise is undertaken, it is beneficial to find all signals oscillating with the common period as the root cause generally lies within this set. The recently proposed autocorrelation function (acf) based method (Thornhill *et al.*, 2003) identified 26 other variables that oscillate with a similar time period as the condenser level $LI1$. These variables and the plant-wide nature of the oscillations is shown in Figure 5. Oscillations produced by the nonlinearities present in control valves (*e.g.*, dead band, backlash, stiction) are often responsible for plant wide oscillations. Therefore, all the control valves, that oscillate with a time period similar to the condenser level, were tested for possible presence of nonlinearities using the higher order statistics based method (Choudhury *et al.*, 2004*c*) applied on the regular operating data. Based on this analysis, it was suspected that the pressure loop ($PC1$ in Figure 5) suffers from stiction and is the root cause of the plant-wide oscillations. This pressure loop controls the level of the condenser by manipulating the coolant flow rate to the condenser. The reader is referred to (Kariwala *et al.*, 2004) for further details on the detection and diagnosis results.

The pressure loop $PC1$ is critical for plant operation and thus it is not possible to put this loop in manual. When the controller gain of this loop was increased, it was found that the frequency of oscillations in the condenser level increased significantly (see Figure 6). Such a behavior is expected from the simulation study and the describing function analysis discussed earlier. This simple test confirmed the presence of stiction in the control valve that manipulates the flow rate of the coolant. Figure 6 shows that the amplitude of oscillations in the condenser level $LI1$ decreased due to the increased controller gain. Presently, the process is being operated with increased controller gain and the control valve for the loop $PC1$, i.e., the coolant flow rate control valve, is scheduled for maintenance during the next plant shutdown.

7. CONCLUSIONS

Control valve stiction can produce limit cycle oscillations causing sub-optimal operation and economic losses. A simple closed loop test for confirming the presence of stiction in control valves has been presented in this paper. The test is based on the observation that changing controller gain also changes the frequency of the oscillations induced in the control loop due to stiction. The method has been extensively evaluated on simulation examples as well as an industrial case study.

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