

Detection and Diagnosis of Plant-wide Oscillations*

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Abstract

This paper presents some emerging techniques for detection and root-cause diagnosis of plant-wide oscillations, and demonstrates their efficacy through a successful industrial case study. The recently proposed autocorrelation function based method (Thornhill *et al.*, 2003a) is used for detection of oscillations in the process measurements. Signals having common oscillations are analyzed for the presence of valve stiction using higher order statistical methods (Choudhury *et al.*, 2004b). A method employing changes in controller gain is proposed for distinguishing an internally generated oscillation from an external oscillatory disturbance. This method of changing controller gain is used to confirm the presence of control valve stiction. All these techniques have been used successfully to identify the root cause of plant-wide oscillations in an industrial case study using routine operating data.

Keywords: Autocorrelation, Chemical industry, Control loops, Control valves, Diagnosis, Fault diagnosis, Nonlinearity, Oscillation, Static friction.

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1 Introduction

Oscillations are a common form of plant-wide disturbance. The presence of oscillations in a control loop increases the variability of the process variables thus causing inferior quality products, larger rejection rates, increased energy consumption and reduced average throughput. The high level of energy integration in most modern plants facilitates the propagation of oscillations from one process unit to another. It is important to detect and diagnose the causes of oscillations in a chemical process because a plant running close to product quality limits or operating constraints is more profitable than a plant that has to back away due to the amplitude of the oscillations (Martin *et al.*, 1991; Shunta, 1995). In this paper, we present an overview of some emerging techniques for the detection and diagnosis of plant-wide oscillations and demonstrate their efficacy through their application to a process at Mitsubishi Chemical Corporation, Mizushima, Japan.

Before a full scale diagnosis exercise is undertaken, it is beneficial to find all signals oscillating at the same frequency as the root cause generally lies within this set. In contrast to this, most of the available techniques for detection focus on a loop by loop analysis (Hägglund, 1995; Taha *et al.*, 1996; Miao and Seborg, 1999). Recently, Thornhill and co-workers have presented some detection tools that consider the plant-wide nature of oscillations (Thornhill *et al.*, 2003b). To detect oscillations in process measurements and identify signals with common oscillatory behavior, use of spectral principal component analysis (Thornhill *et al.*, 2002) or autocorrelation functions (acf) (Thornhill *et al.*, 2003a) is suggested. Recently, Xia and Howell (2003) have also proposed a technique that takes the interactions between control loops into account. Some other related studies have been performed by (Ettaleb *et al.*, 1996; Ettaleb, 1999; Forsman, 1998). In this paper, we use the acf based method as it reduces the effect of noise, handles multiple oscillations in the same measurement easily and also provides the time periods of the different oscillations.

In a control loop, oscillations may arise for various reasons including poorly tuned controllers, presence of oscillatory disturbances and nonlinearities. Bialkowski (1992) reported that about 30% of the loops are oscillatory due to control valve problems. In a recent industrial survey, Desborough and Miller (2001) 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. In addition to invasive studies for the analysis of control valve performance (Taha *et al.*, 1996; Wallén, 1997; Sharif and Grosvenor, 1998; Gerry and Ruel, 2001), a few non-invasive methods (Horch, 1999; Rengaswamy *et al.*, 2001; Stenman *et al.*, 2003; Choudhury *et al.*, 2004b; Kano *et al.*, 2004; Choudhury *et al.*, 2004a; Choudhury, 2004; Singhal and Salsbury, 2005; Rossi and Scali, 2005) have also appeared in the literature. In this paper, we demonstrate the efficiency of Higher Order Statistical methods (Choudhury *et al.*, 2004b) in combination with *pv-op* plots, that are useful for analyzing signals having common oscillatory behavior for possible valve problems from closed-loop operating data. For the present case study, the proposed strategy successfully identifies the key variables that are most likely root causes of oscillations.

Higher Order Statistical techniques (Choudhury *et al.*, 2004b) and other 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 valve may generate limit cycle oscillations that can easily propagate to other loops in 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 only those valves that 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. The valve is confirmed to be sticky, if the limit cycle of the oscillation dies out, as a limit cycle only arises as a result of feedback. In many cases including the case study considered here, it is not possible to put the loop in manual due to reasons of safety, disruption in plant production and undesirable effect on other loops. Therefore, a test that does not require putting the loop in manual and one which can be applied online under closed-loop conditions, is invaluable for the process industries. In this paper, we describe a simple test employing changes in controller gain for confirming stiction in control valves and show its application to an industrial case study.

Using these techniques, we were able to detect and identify the control valve that gave rise to plant-wide oscillations. When this sticky valve was fixed during the scheduled plant maintenance, the oscillation disappeared confirming our analysis. In summary, the use of following steps successfully diagnosed the root cause of the plant-wide oscillations for the industrial case study:

1. Oscillation detection via the autocorrelation function (acf) based method (Thornhill *et al.*, 2003a).
2. Root cause diagnosis via higher order statistical method (Choudhury *et al.*, 2004b) for identifying key variables likely to be the root cause.

3. Confirmation of root cause based on changes in controller gain for confirming the presence of stiction.

It is pointed out that the method based on these steps is quite general for finding the root cause of oscillations due to valve stiction, which is known to be the key reason for oscillations in process industries (Bialkowski, 1992; Desborough and Miller, 2001). The attraction of this method is that it primarily uses only regular operating data followed by a simple closed-loop test. The main contributions of this paper are:

1. Automatic detection of multiple oscillations across an entire plant site.
2. Demonstration of the potential of Higher Order Statistical methods and the *pv-op* plot (as a secondary step) for diagnosing root cause of plant-wide oscillations.
3. A systematic study on the simple closed-loop method employing controller gain change to distinguish an internally generated oscillation from an external oscillatory disturbance, hence confirming the presence of valve stiction.
4. A detailed describing function analysis is provided for theoretical support of the controller gain change method.
5. Demonstration of the potential of systematic use of the proposed combination of signal processing techniques for solving industrial problems through a case study.

The novelty of this paper lies on the last four contributions listed above.

2 Problem Description

The process under investigation here is the plant at Mitsubishi Chemical Corporation, Mizushima, Japan. The plant personnel reported large amplitude oscillations 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. The aim of the study was to find an explanation for the oscillations in the condenser level.

Scope of analysis There are a large number of variables in the process and a sequential approach is used to define the scope of the analysis. Starting from the condenser level, the scope of the study is expanded

based on mass, energy and information connectivity (based on controller structure) of the process until no more oscillations are detected. For this preliminary analysis, visual inspection of time trends and spectra were found to be sufficient.

Data set Based on the preliminary analysis, the final data set is chosen to consist of 43 tags. These tags are taken from various process units shown in Figure 1. The condenser which is at the center of the study is located at the top left of the figure. 15 of these variables are controlled using PI(D) controllers and the controller outputs for these variables are also included in the study. For these variables, a sample data set consisting of 2880 samples was collected at the rate of 1 sample/minute, which corresponds to data over 2 days of operation.

In Figure 1 and the ensuing discussion, the notation used for tags is standard in process industries. AC, FC, LC, PC and TC represent composition, flow, level, pressure and temperature tags, respectively, that are controlled. Similarly, FI, LI, SI and TI represent the flow, level, rotor speed and temperature tags, respectively, that are indicators only. The set point, process variable and controller output are denoted as sp , pv and op , respectively.

3 Oscillation Detection

This section briefly reviews the acf based method followed by the results obtained by its application to the industrial data set.

3.1 Methodology

The power spectrum (spectra) of a signal shows peaks at underlying frequencies of the signal. Whereas presence of peaks in the spectra is sufficient for judging whether a signal is oscillatory or not, calculation of the time period can be difficult due to the presence of noise. The knowledge of the time period is useful for identifying signals having common oscillatory behavior. For this purpose, Thornhill *et al.* (2003a) proposed the use of acf based method, whose key features follow:

- Let \bar{T}_p , σ_{T_p} be the mean and standard deviation of the zero crossings of acf. Then the signal is

considered to be oscillating with time period \bar{T}_p if

$$\bar{T}_p > 3\sigma_{T_p} \quad (1)$$

Presence of multiple oscillations can destroy the regularity of zero crossings of the acf. In this case, the test is applied to the signal filtered using an ideal band pass filter having zero gain outside the selected frequency range.

- To avoid insignificant detections, the test in (1) is only applied, if the filtered signal has sufficient fractional power defined as

$$P = \frac{\sum_{n=\omega_{n_1}}^{\omega_{n_2}} \Phi(i\omega_n)}{\sum_{n=0}^{\pi} \Phi(i\omega_n)} \quad (2)$$

where $\Phi(\cdot)$ is the power spectrum, and ω_{n_1} and ω_{n_2} denote the lower and upper boundaries of the filter, respectively. A low value of P indicates that the signal does not have significant activity in the selected frequency band or in other words, the behavior of the signal is dominated by other frequencies. Thornhill *et al.* (2003a) suggest a threshold value of 1% for P , but higher values can be used to avoid detection of insignificant oscillations.

- The acf based oscillation detection method can easily be automated. The underlying idea is to first remove the non-stationary trends of the data. Then the statistical test in (1) is used to detect the oscillations in the process measurements. A simple heuristic based clustering algorithm is used to find all signals having a common oscillation period. The search continues by narrowing the filter ranges around the oscillations detected in the previous step. The algorithm terminates when at most one oscillation is detected in every filter range or the filter ranges become too narrow.

Though useful, the acf based method has some limitations, which were revealed during the application of this method to the industrial data set. Here, the source of these limitations and the simple strategies adopted to overcome them are discussed briefly.

1. The acf based method is prone to false detections. The algorithm uses ideal band pass filters. If it is a narrow band pass filter, the filtered data may be oscillatory and the algorithm may provide misleading results. This difficulty can be overcome by using the Hanning window, but this increases the complexity of the algorithm. In this paper, the oscillations detected close to the filter boundaries are verified against the peaks present in the spectra. We also widen the filter range and repeat the analysis to distinguish between a false detection and a true oscillation present close to filter boundaries during every iteration.

2. The presence of noise, non-stationary trends and multiple oscillations may destroy the regularity of the zero crossings of the acf. In this case, the automated algorithm may detect (generally during first iteration) none or only one oscillation causing premature termination, despite the spectrum showing multiple distinct peaks. For the case, when a single oscillation is detected, artificially narrowing down the filter ranges around the detected oscillations is found to be helpful.

Note that the presence of these limitations inhibits the automation of the acf based detection methodology. The method can be used in a semi-automated fashion (as done here) with the suggested heuristics. The determination of more reliable and simpler remedies is an issue for further research.

3.2 Oscillation Detection Results

For the industrial case study, the data set is filtered to remove the low frequency non-stationary trends, such that any trends less than 8 complete cycles in the data are removed. Then, the acf based method is applied on the filtered data set. The results of the detection analysis are summarized in Table 1 and the key characteristics are discussed below:

- The condenser level (LI1) oscillates with a period of approximately 158 samples/cycle with a fractional power of 88% as given by Equation (2). Thus 158 samples/cycle is taken as the fundamental time period for the purposes of this study.
- The algorithm also detects 26 other variables that oscillate with a similar time period as the condenser level. Among these variables, 17 variables have fractional power of 40% or more, which require immediate attention.
- 10 variables oscillate with a time period of approximately 137 samples/cycle. Note that it is difficult to distinguish these variables from those oscillating with the time period of 158 samples/cycle through direct visualization of the power spectrum.
- Considering 158 samples/cycle to be the fundamental time period, it is noted that a number of the variables exhibit harmonics (approximately 79 samples/cycle). This indicates the presence of non-linear elements (*e.g.* valve stiction, deadband or other nonlinearities) in the process.
- The algorithm also detects a fast oscillation with a period of 4 samples/cycle in the variable FI4. This oscillation is traced to a hardware fault in a separate study.

The variables affected by low frequency oscillations with a power of 10% or more are shown in Figure 1, where the plant-wide nature of the oscillations should be noted. Due to presence of high heat integration and a multivariable controller, which acts as a supervisory controller, it is difficult to diagnose the root cause of oscillations through a cause-effect analysis. A systematic analysis is discussed in the following sections.

4 Oscillation Diagnosis

There are several reasons that may cause a control loop to oscillate, for example poorly tuned controllers, presence of oscillatory disturbances and/or nonlinearities. Control Loop Performance Assessment (CLPA) (Desborough and Harris, 1992) is a convenient method to assess the *goodness* of controller tuning. A controller is termed as well tuned if the controller error signal has little or no predictable component and *vice versa*. For the present case study, use of CLPA provides no clear indications that the oscillations are caused due to poorly tuned controllers.

Controllers that are tuned too tightly start to oscillate close to their unity-gain cross-over frequency. Oscillations such as those arising due to poor controller tuning usually have a time period of the order of a few minutes. On the other hand, process nonlinearities, *e.g.* valve stiction introduces phase lag which slows down the limit cycle oscillation. As the order of the time period of the oscillation detected in the condenser level is much larger than a few minutes, the possibility of oscillation due to poor controller tuning was ruled out. Moreover, the higher order statistical method, as discussed later, was used to detect nonlinearities in control loop. A tightly tuned controller may produce oscillation in a loop, but does not introduce any nonlinearity. Thus, higher order statistical methods do not detect such loops as nonlinear (Choudhury *et al.*, 2004b). In the following discussion, we present the method aimed at detecting nonlinearities in the control valves with primary focus on valve stiction.

4.1 Nonlinearity Detection

Oscillations produced by the nonlinearities present in control valves (*e.g.*, deadband, backlash, stiction) are often responsible for plant-wide oscillations. Recently, Thornhill *et al.* (2003b) showed that a deadband in the process valve can give rise to severe process oscillations. Thornhill *et al.* (2003b) used a surrogate test data based method (Theiler *et al.*, 1992) for detecting nonlinearity in the process measurements. We

next describe a simpler method using Higher Order Statistics developed by Choudhury *et al.* (2004b). The method consists of two steps, both of which are discussed below.

1. *Higher Order Statistical Method:* The method is based on presence of phase coupling in a non-linear time series. These phase couplings can be detected by the bicoherence of the signal defined as:

$$bic^2(f_1, f_2) \triangleq \frac{|E[X(f_1)X(f_2)X^*(f_1 + f_2)]|^2}{E[|X(f_1)X(f_2)|^2]E[|X(f_1 + f_2)|^2]} \quad (3)$$

where $X(f_1)$ is the discrete Fourier transform calculated at the frequency f_1 , $X^*(f_1)$ is the complex conjugate and E is the expectation operator. The bicoherence is the normalized bispectrum and has a value between 0 and 1, where a non-zero value results only if there is significant phase coupling in the signal between frequency components at f_1 and f_2 .

In Choudhury *et al.* (2004b), two indices - the Non-Gaussianity Index (*NGI*) and the Non-Linearity Index (*NLI*) have been defined based on the bicoherence. When both *NGI* and *NLI* are greater than zero, the signal is described as non-Gaussian and nonlinear and it is inferred that the loop in question exhibits significant non-linearity. For a control loop, this test is applied on the error signal ($sp - pv$) as the error signal is often more stationary than pv or op signals. Assuming that the process is linear and no nonlinear disturbances enter the loop, the nonlinearity can be attributed to the control valve.

2. *Use of pv - op Plot:* Once a nonlinearity is detected using higher statistical analysis-based *NGI* and *NLI* indices, the pv - op plot is used to diagnose and isolate its cause. It is well known (Hägglund, 1995; Horch, 1999; Ruel, 2000; Rengaswamy *et al.*, 2001) that the presence of stiction in control valve in a control loop produces limit cycles in the controlled variable (pv) and the controller output (op). For such a case, the pv - op plot shows cyclic or elliptic patterns, which are taken as a signature of valve stiction. If no such patterns are observed, it is concluded that there may be valve problems other than stiction.

4.2 Quantifying Stiction

It is important to be able to quantify stiction so that a list of sticky valves in order of their maintenance priority can be prepared. A segment of the data that has regular oscillations is used for the construction of the pv - op plot. An ellipse in the least square sense is fitted to the pv - op plot and is used for quantifying stiction. The apparent stiction is defined as the maximum width of the ellipse along the op axis. Then,

the distance between two points lying on the intersections of the ellipse and a line parallel to the op axis and passing through the center of the ellipse will be the amount of stiction present in the loop. If m and n are the length of the major and minor axes of the fitted ellipse respectively, and α is the angle of rotation of the ellipse from the positive x -axis, then the amount of stiction is obtained using the following expression (Choudhury *et al.*, 2004a; Choudhury *et al.*, 2006):

$$\text{Apparent Stiction}(\%) = \frac{2mn}{\sqrt{(m^2 \sin^2\alpha + n^2 \cos^2\alpha)}} \quad (4)$$

The quantified stiction is termed as *apparent stiction* because the actual amount of stiction to be obtained from the $mv-op$ plot may differ from the estimated quantity because of the role of the controller in attempting to regulate the process variable.

4.3 Confirming Stiction

Though stiction detection methods are useful in short-listing the sticky valves, they have some limitations, as discussed in Section 1. Due to these limitations, usually a plant test is required to confirm if the suspected valves are indeed suffering from stiction. Here, a method based on changing the controller gain under closed-loop control configuration is discussed.

The various methods for confirming valve stiction are (i) the valve travel or bump test, (ii) use of valve positioner data and, (iii) changes in controller gain. The valve travel test (Taha *et al.*, 1996; Wallén, 1997; Gerry and Ruel, 2001) requires that the loop be put in manual. This method is not convenient and cost-effective due to the risk of plant upset and production of more ‘off-spec’ products. Similarly, the valve positioner data is rarely available in practice (except for smart valves), which restricts the application of this simple test to only a few cases.

A simple alternative test that can be applied online without affecting the plant production significantly, is based on the controller gain change. The 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 the oscillation frequency due to variation in controller gain confirm the presence of stiction in the loop.

It appears that this simple test employing changes in controller gain may be known to engineers in the process industries, but is relatively less well-known in academia. This simple test was first reported in

(Thornhill *et al.*, 2003b) where an online closed loop plant test was conducted to confirm the presence of stiction. The influence of gain change on the amplitude and frequency of oscillations due to stiction has also been described briefly through a simulation study in (Choudhury *et al.*, 2005). Later Rossi and Scali (2005) reported the phenomenon of change of oscillation frequency due to the change of controller gain as an observation. In this work, a simulation study of this phenomenon has been carried out to distinguish stiction induced oscillation from an external oscillatory disturbance. A theoretical justification through describing function analysis is also presented.

4.3.1 Simulation study for distinguishing stiction from external oscillatory disturbance

This section demonstrates the effect of changing controller gain on the closed loop behavior of a control loop in the presence of a sticky valve. A two parameter stiction model developed in (Choudhury *et al.*, 2005) was used to introduce the stiction behavior of the control valve in the closed loop process. The two parameters are deadband plus stickband (S) and slip jump (J), which are taken as 3% and 1%, respectively, for all simulations. The PI controllers used in all simulations were implemented in the following form:

$$C(s) = K_c \left(1 + \frac{1}{\tau_i s} \right) \quad (5)$$

The controller gains and reset times are reported in the right column of each figure provided for the following cases.

A concentration control loop with a sticky valve The transfer function model for this loop is similar to the one reported in Horch and Isaksson (1998) except the time delay has been reduced to 5 for better control of the process:

$$G(s) = \frac{3e^{-5s}}{10s + 1} \quad (6)$$

The model in (6) describes the dynamics of mixing pulp with water from the inlet of the water flow control valve to the outlet of a mixing chamber (Horch and Isaksson, 1998). The top row in Figure 2 shows that during normal operation there is no limit cycles with the existing controller settings reported in the right column of the figure. In the presence of stiction, a limit cycle oscillation with a period of 98 sec generated in the loop (the plot in the second row of Figure 2). In order to confirm that this oscillation is generated within this loop, the controller gain was reduced by 50%, which in turn decreases the frequency of oscillation. The third row in the figure shows that the oscillation period is now approximately 198 sec

and the amplitude of the oscillation is also decreased. Reducing the gain further decreases the frequency of oscillation. This test confirms that this oscillation is internally generated.

A level control loop with a sticky valve The transfer function for this level loop was an integrator of the form of $\frac{1}{5s}$. Figure 3 shows the result of changing controller gain, K_c . The plot in the first of the figure shows that during normal operation there is no oscillation. The plots from the second to the fourth row in Figure 3 shows that an decrease in controller gain for the level loop decreases the frequency of oscillation but increases the amplitude of oscillation.

Connected concentration and level loop The purpose of this case is to present the technique of distinguishing internally generated oscillation or within loop oscillation from an external oscillatory disturbance to a control loop. This simulation case has been formulated by feeding the output of the concentration loop as a disturbance to the level control loop. Stiction is now only present in the concentration loop valve and there is no stiction in the level control valve. In reality, this describes a scenario where the outlet of a mixing chamber in a concentration 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 oscillates because the oscillation due to the presence of stiction in the concentration loop control valve propagates to the level loop. 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.*, 2004b) will detect stiction in both loops because all of the algorithms work on a single loop basis only and do not consider the interaction among the loops, especially this kind of propagated oscillation. The method of controller gain change is applied to differentiate between the loops suffering from stiction and the loops oscillating due to propagated oscillatory disturbances.

The results for this case are shown in Figure 4. In the case of normal operation, there were oscillation neither in the concentration loop nor in the level loop (plots in the top row). Then, due to the introduction of valve stiction in the concentration loop control valve, an oscillation with a period of 46 sec is generated in the concentration loop and it propagates to the level loop. All stiction detection algorithms described earlier will detect stiction in both loops. In order to confirm the presence of stiction in these loops, the proposed gain change method can be applied. If the gain of the concentration loop controller is decreased by 50%, the frequency of the oscillation in the concentration loop decreases to 94 sec/cycle, which in turn decreases the frequency of oscillation in the level control loop too (the third row in Figure 4). But when the gain of the level controller is decreased by 50%, the frequency of oscillation in the level loop does not

decrease further, rather it remains constant. This confirms that the oscillation in the level loop is not internally generated rather it enters the loop as an external disturbance. Therefore, the level control valve is not suffering from stiction.

Conclusions from the simulation study 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 set-point excitation. Based on this simulation study, the following conclusions can be drawn:

- If a limit cycle oscillation is generated internally within a loop due to valve stiction, a change in controller gain will change the frequency of oscillation.
- If a limit oscillation enters the control loop as an external disturbance, a change in controller gain will not change the frequency of oscillation.

Remark 1: If the oscillations in a loop start due to a tightly tuned controller, a decrease in controller gain would decrease the frequency of oscillation. This will only prove that this oscillation is internally generated but would not be able to detect whether it is due to stiction or due to a tightly tuned controller. Therefore, in order to distinguish between these two cases, one must use a stiction detection method. Since the presence of a tightly tuned controller does not introduce any nonlinearity in a control loop, the higher order statistical method will eliminate this loop as a linear loop in its first diagnostic step. For a detailed discussion see Choudhury *et al.* (2004b). After detection of stiction, the gain test method will help to isolate the valve(s) suffering from stiction.

Remark 2: In practice, it is not necessary to change the controller gains two or four times. A change in controller gain by any significant amount should do the job. The central idea is to observe whether a change in controller gain causes a change in frequency of oscillation. If it does, then it can be concluded that the oscillation is internally generated within the loop. If valve saturation is a concern, reduction of controlled gain can be preferred.

4.3.2 Describing Function Analysis

In this section, describing function analysis is used to provide a theoretical justification for the observed closed loop behavior due to changes in controller gain. In order to improve the readability of the paper, a summary of the describing function analysis of two parameter stiction model is provided below. For details, readers are referred to ((Choudhury *et al.*, 2005; Choudhury, 2004)).

A non-linear actuator with a stiction characteristic may cause limit cycling in a control loop (Choudhury *et al.*, 2005). 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:

$$L_o(i\omega) = -\frac{1}{N(X_m)} \quad (7)$$

where $L_o(i\omega) = G(i\omega)C(i\omega)$ is the loop gain evaluated at frequency ω , and $N(X_m)$ is the describing function which depends on the magnitude of the controller output, X_m . When condition (7) 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-induced 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 $L_o(i\omega)$ and $-1/N(X_m)$ on the same set of axes. The aim of describing function analysis is to gain insight into the simulation results and industrial observations presented in this paper. The describing function for the two parameter stiction model as provided in (Choudhury *et al.*, 2005; Choudhury, 2004) is:

$$N = -\frac{1}{\pi X_m} (A - iB) \quad (8)$$

where

$$A = \frac{X_m}{2} \sin 2\phi - 2X_m \cos \phi - X_m \left(\frac{\pi}{2} + \phi \right) + 2(S - J) \cos \phi, \quad (9)$$

$$B = -3\frac{X_m}{2} + \frac{X_m}{2} \cos 2\phi + 2X_m \sin \phi - 2(S - J) \sin \phi \quad (10)$$

$$\phi = \sin^{-1} \left(\frac{X_m - S}{X_m} \right) \quad (11)$$

where X_m is the input to the control valve or the controller output (*op*), S is the deadband plus stickband and J is the slip-jump.

Figure 5 shows the graphical solutions of Equation (7) for the concentration control loop and level loop. The systems are 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 for both cases. It is clear from Figure 5 that there will be limit cycles for both loops 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 predicts that an increase in controller gain will increase the frequency of limit cycle oscillation and conversely a reduction in the gain will reduce the frequency of limit cycle oscillation.

Comparison of Describing Function Analysis (DFA) Results with Simulation Results

Figure 6 compares the frequencies and amplitudes of limit cycles predicted by DFA with those obtained from simulation. Frequencies of limit cycles predicted by DFA are in good agreement with those obtained from simulation for both loops. Amplitudes predicted by DFA for level loop are also very close to those obtained from simulation. However, for the concentration loop the amplitudes predicted by DFA differs with that obtained from simulation for the cases of higher controller gains. This may arise due to possible multiple equilibrium points for the concentration loop system at high controller gain. The other differences in frequency and amplitudes are probably due to the approximate nature of DFA analysis. The DFA approximates the limit cycles as a pure sinusoid with one fundamental frequency and neglects all other higher harmonics. But in reality, the limit cycles caused by a sticky valve is not a pure sinusoid and its shape changes with the change of controller gains.

4.4 Oscillation Diagnosis Results for the Industrial Case Study

The higher order statistics based NGI and NLI indices were calculated for the variables of control loops that oscillate with the same time period as condenser level and the results are shown in Table 2. It is clear from Table 2 that only three loops, namely FC5, PC1, and TC2 show nonlinear behavior. Figure 7 shows the bicoherence plots for these loops. A large peak in the bicoherence plot represents significant nonlinear interactions between those two frequencies of the signal. It is clear from Figure 7 that in each of the loops there are significant nonlinear interactions.

These nonlinear loops were further investigated using the *pv-op* plot. For the FC5 loop, the *pv-op* plot does not show any pattern (see the left plot of the second row in Figure 7). As is confirmed by using CLPA (Desborough and Harris, 1992; Huang and Shah, 1999), this loop contains a hardware fault. Analysis of PC1 loop shows that the valve has approximately 0.5% stiction. The right plot in the second row of

Figure 7 shows the presence of 1.25% stiction in the valve for the TC2 loop. Based on this analysis, we conclude that one or both of the loops PC1 and TC2 is most likely the root cause of the oscillations.

The limit cycles produced by TC2 must pass through different process units before affecting the condenser level. This observation implies that PC1 is the most likely cause of the oscillations and it was decided to apply the gain change test on the controller of the PC1 loop for confirming the presence of stiction. It was communicated to us by the plant personnel that the pressure loop PC1 is critical for plant operation. Thus it was not possible to put this loop in manual and perform the valve travel or bump test for confirming stiction.

When the controller gain of the PC1 loop was increased, it was found that the frequency of oscillations in the condenser level increased significantly (see Figure 8). Before the gain change the frequency of oscillation was approximately 154 samples/cycles or 0.0068 cycles/sample and after the gain was doubled the frequency increased to 63 samples/cycles or 0.016 cycles/sample (see the power spectrums in Figure 8). The amplitudes of oscillations also decreased with the increase of controller gain. Time trends shown in Figure 8 were normalized with the standard deviation of the respective data before the gain change for both cases (before and after gain change). This phenomena 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. Figure 8 shows that the amplitude of oscillations in the condenser level LI1 decreased due to the increase in the controller gain.

4.4.1 PC1 and LI1 loops after fixing the sticky valve during the overhauling of the Plant

During the shutdown maintenance period of Summer 2005, the control valve for the PC1 loop was repaired and cleaned. After the resumption of the plant operation, the MPC controllers were also retuned. Figure 9 shows the new time trends and the power spectrum of the data corresponding to PC1 and LI1 loops. The figure shows that the previous oscillation at the frequency 63 samples/cycles or 0.016 cycles/sample (see the power spectrums in Figure 8) is now gone. Both loops are operating satisfactorily. By comparing the power spectrums of Figures 8 and 9, it is clear that the power of all oscillations has been reduced significantly. The small peak in the power spectrum of LI1 in Figure 9 is due to a low frequency oscillation (200 samples/cycle) probably caused by interaction from other loops. Note that this peak was also present, but somewhat overshadowed by larger peaks, in Figure 8. This case study has thus confirmed the utility and practicality of the proposed detection and diagnosis procedure for valve stiction.

5 Conclusions

Despite its significant economic incentives, detection and diagnosis of plant-wide oscillations has received limited attention from researchers. This paper has demonstrated the utility of some emerging techniques for root cause analysis of oscillations due to valve stiction through an industrial case study. A simple test involving a controller gain change has been described to distinguish an internally generated oscillation from an external oscillation. It has been used in conjunction with higher order statistical indices, *NGI* and *NLI*, to confirm the presence of stiction in a control valve. The procedure was applied to detect and confirm the presence of valve stiction in an industrial case study. Finally, the oscillation was successfully removed after the sticky valve was fixed during the scheduled plant maintenance period. Many other issues, such as the effect of interacting control loops, still need to be resolved before a fully-automated method becomes available for root cause analysis of plant-wide oscillations.

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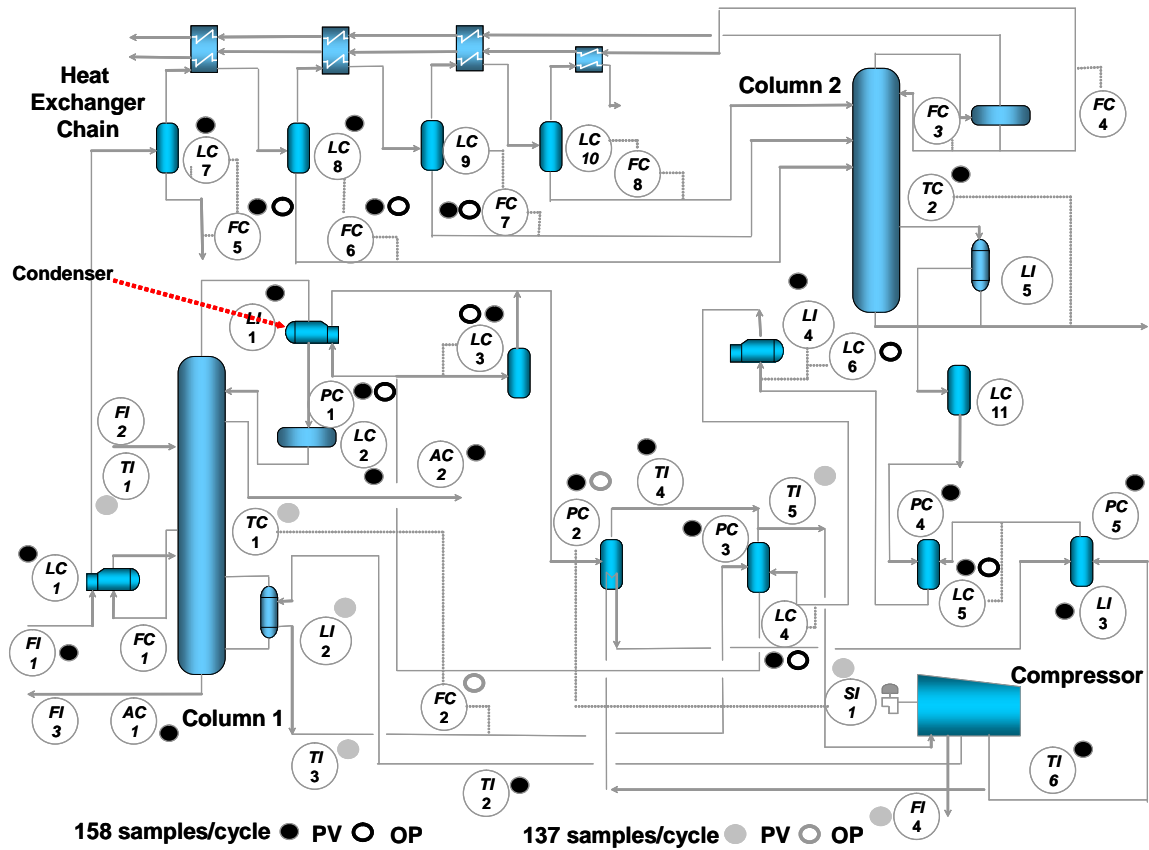


Figure 1: Process flow diagram showing detected oscillations in low frequency range (88 - 183 samples/cycle)

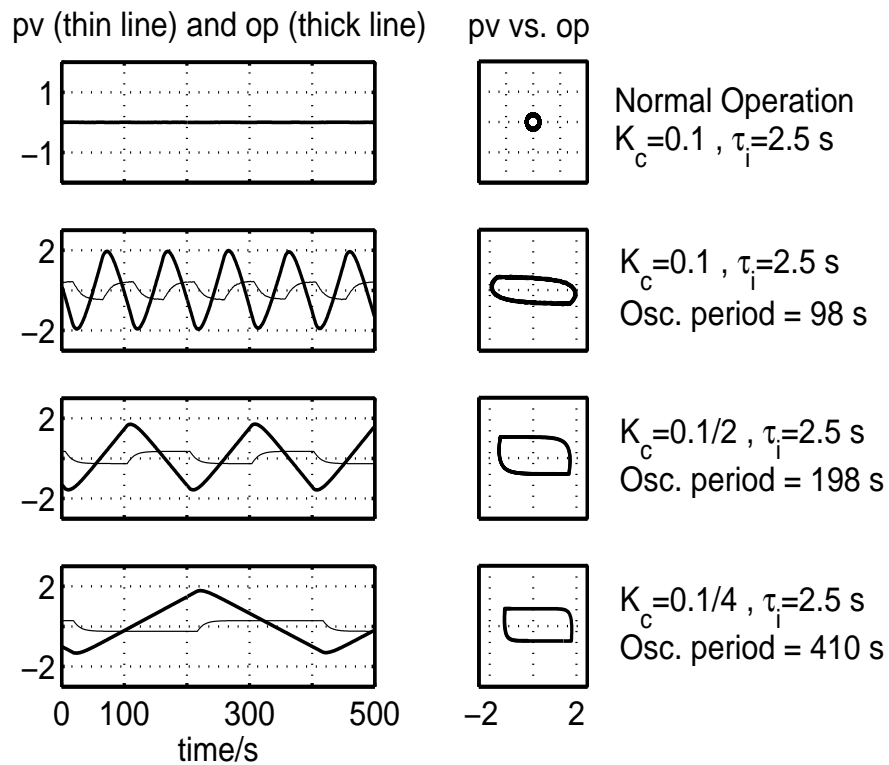


Figure 2: *Effect of changing controller gains on the limit cycles generated by a sticky valve in a concentration loop. A decrease in controller gain causes a decrease in frequency and amplitude of the limit cycles.*

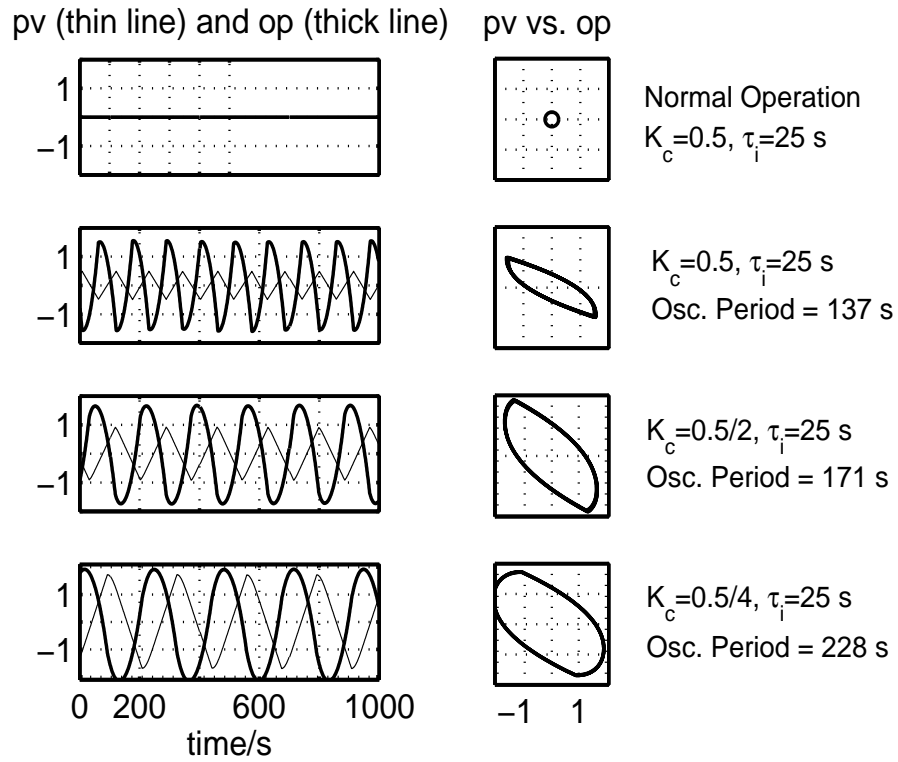


Figure 3: *Effect of changing controller gains on the limit cycles generated by a sticky valve in a level loop. A decrease in controller gain causes a decrease in frequency, but an increase in amplitude of the limit cycles.*

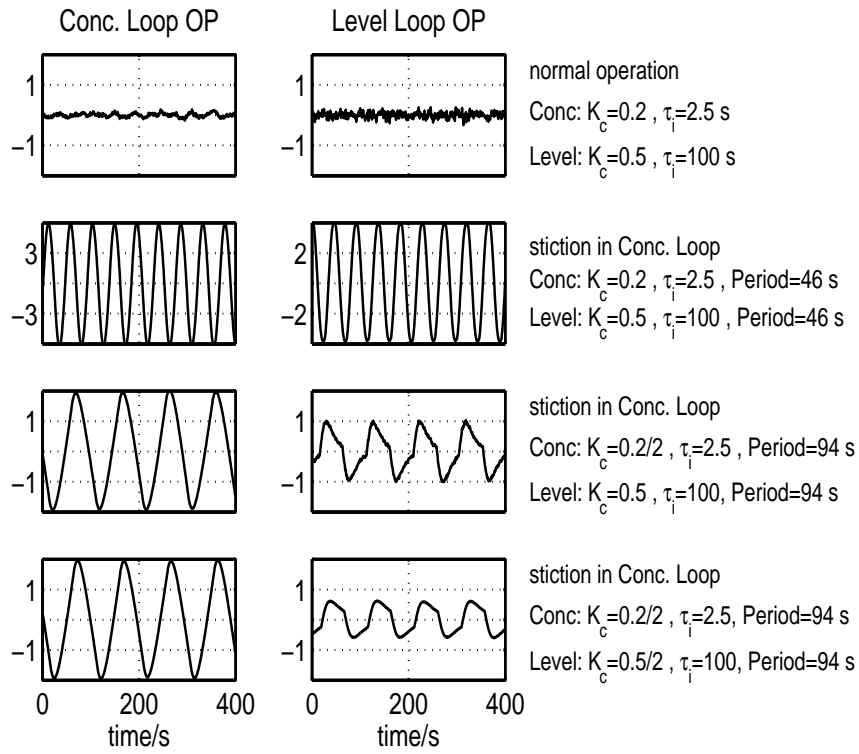
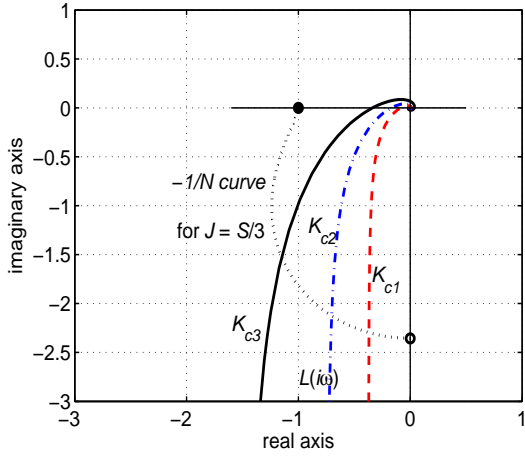
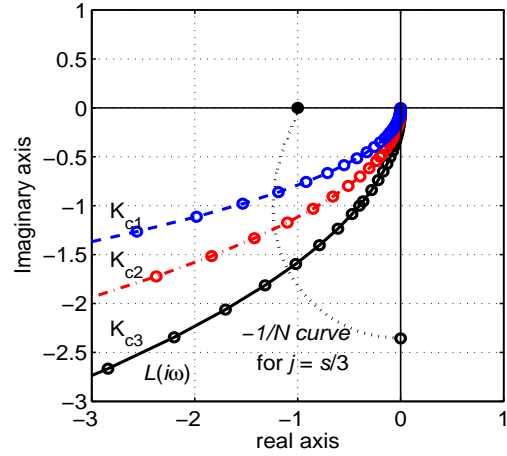


Figure 4: *Stiction causes oscillation in concentration control loop and this oscillation propagates to level control loop. A change in controller gain in concentration loop causes a change in frequency of oscillation but the change in level controller gain does not cause any change in frequency of oscillation.*

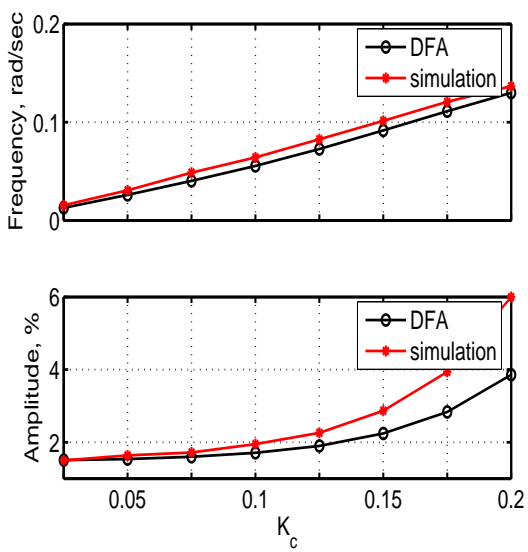


(a) Concentration Loop

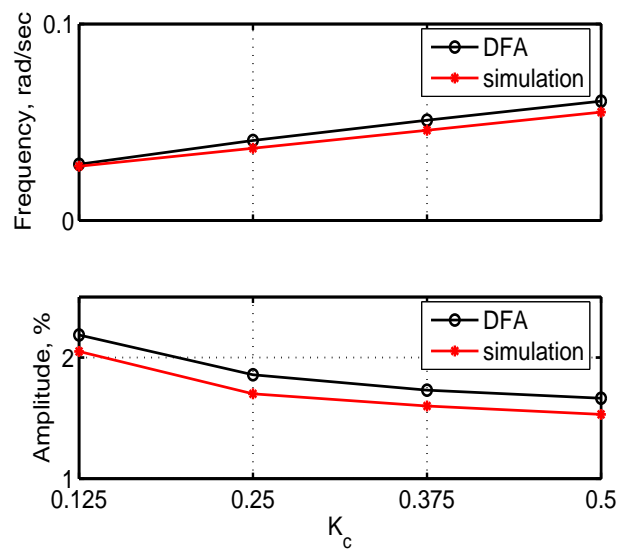


(b) Level Loop

Figure 5: Graphical solutions for limit cycle oscillations. The 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, $L_o(i\omega)$. Concentration Loop: Gains are $K_{c1} = 0.025 < K_{c2} = 0.05 < K_{c3} = 0.1$ and reset time is $\tau_i = 2.5$ s. Level Loop: Gains are $K_{c1} = 0.125 < K_{c2} = 0.25 < K_{c3} = 0.5$ and reset time is $\tau_i = 25$ s



(a) Concentration Loop



(b) Level Loop

Figure 6: Comparison of frequencies and amplitudes of limit cycle oscillation as predicted by Describing Function Analysis with those obtained from Simulation.

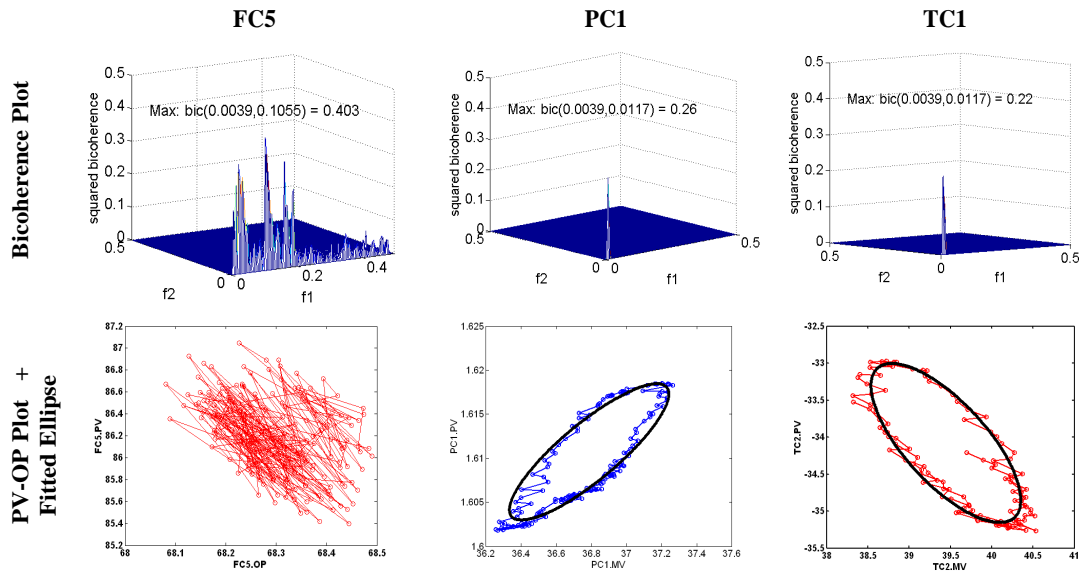


Figure 7: *Bicoherence and pv-op plots for condenser level oscillation diagnosis*

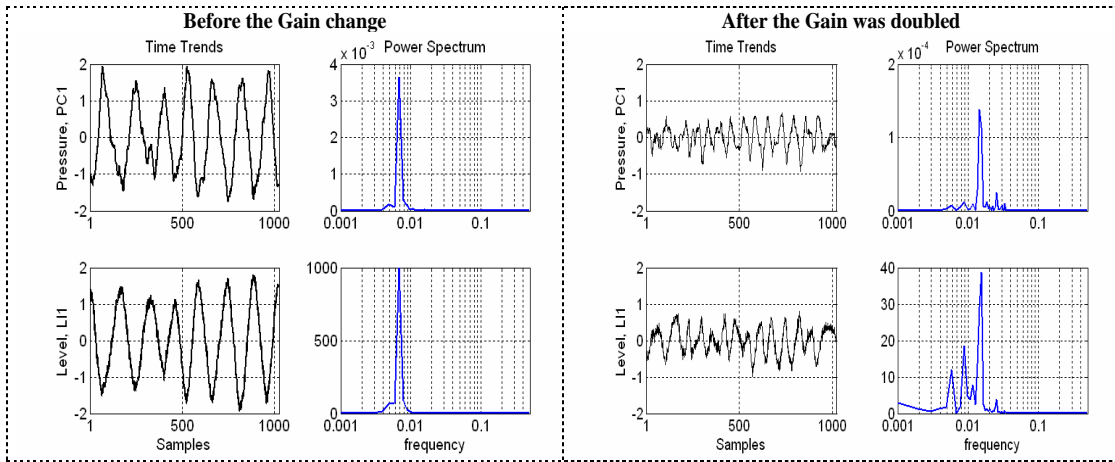


Figure 8: *Effect of changes in controller gain on the oscillatory behavior for the industrial process. The plots in the left column are for before the gain change case and the plots in the right column correspond to after the gain change case.*

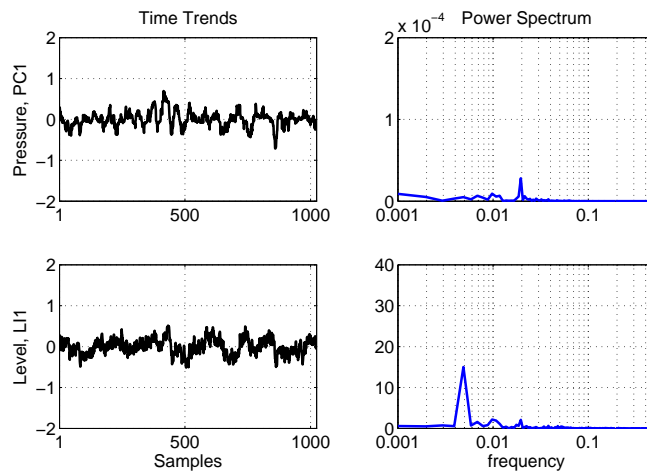


Figure 9: *The pressure PC1 and the level LI1 after the maintenance of the sticky value of loop PC1.*

Tag	High (4-44)		Medium (44-88)		Low (88-183)		Tag	High (4-44)		Medium (44-88)		Low (88-183)	
	Period	P	Period	P	Period	P		Period	P	Period	P	Period	P
<i>Process Variables:</i>													
FI1	-	-	73 ± 18	12	168 ± 30	22	LC1	50 ± 9	9	82 ± 16	10	163 ± 32	52
FI2	-	-	62 ± 5	29	-	-	TI1	-	-	74 ± 2	6	137 ± 18	38
FC1	-	-	-	-	-	-	AC1	-	-	75 ± 2	11	157 ± 14	65
FI3	-	-	-	-	-	-	LI1	-	-	-	-	159 ± 7	90
PC1	-	-	75 ± 2	7	160 ± 13	90	LC2	-	-	75 ± 2	14	161 ± 13	56
AC2	-	-	75 ± 2	14	161 ± 12	60	TC1	41 ± 10	9	75 ± 3	42	140 ± 37	42
LI2	-	-	75 ± 4	11	141 ± 27	50	FC2	-	-	-	-	-	-
TI2	-	-	73 ± 5	17	160 ± 27	11	TI3	43 ± 5	63	73 ± 3	16	144 ± 28	18
LC3	-	-	63 ± 16	9	157 ± 26	10	PC2	-	-	-	-	160 ± 12	77
TI4	-	-	73 ± 7	9	158 ± 8	54	PC3	-	-	80 ± 8	6	159 ± 7	62
TI5	44 ± 3	48	73 ± 16	15	124 ± 36	21	LC4	-	-	63 ± 18	8	161 ± 28	31
PC4	-	-	75 ± 7	9	160 ± 19	51	LC5	-	-	63 ± 18	14	162 ± 25	56
LI3	-	-	-	-	158 ± 8	90	PC5	-	-	-	-	157 ± 7	39
TI6	-	-	73 ± 5	5	155 ± 9	28	FI4	4 ± 1	81	-	-	141 ± 45	12
SI1	-	-	75 ± 3	8	144 ± 42	28	LI4	-	-	-	-	157 ± 6	13
LC6	-	-	73 ± 23	25	-	-	LI5	-	-	63 ± 7	42	108 ± 36	31
TC2	-	-	62 ± 7	22	172 ± 34	29	FC3	-	-	-	-	-	-
FC4	-	-	86 ± 7	17	-	-	LC7	-	-	89 ± 19	7	158 ± 17	44
FC5	-	-	-	-	158 ± 44	6	LC8	-	-	65 ± 17	17	159 ± 16	19
FC6	-	-	65 ± 17	11	159 ± 13	26	LC9	-	-	-	-	-	-
FC7	-	-	-	-	159 ± 20	10	LC10	26 ± 8	86	-	-	-	-
FC8	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Controller Outputs:</i>													
FC1	-	-	-	-	-	-	PC1	-	-	-	-	160 ± 12	77
FC2	-	-	75 ± 4	10	139 ± 19	20	LC3	-	-	75 ± 8	10	157 ± 10	37
PC2	-	-	75 ± 3	8	143 ± 41	28	LC4	-	-	63 ± 18	7	161 ± 21	65
LC5	-	-	76 ± 15	8	162 ± 20	76	LC6	-	-	69 ± 22	10	160 ± 36	26
TC2	-	-	63 ± 6	37	-	-	FC3	-	-	86 ± 23	6	-	-
FC4	44 ± 6	9	85 ± 8	17	-	-	FC5	-	-	-	-	157 ± 10	15
FC6	-	-	65 ± 20	11	159 ± 20	26	FC7	-	-	-	-	158 ± 39	15
FC8	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 1: Oscillation detection summary for controller outputs. The reported oscillations are in the form $\bar{T}_p \pm \sigma_{T_p}$

Tag	NGI	NLI	Apparent Stiction (%)	Remarks
AC1	–	–	–	No control valve
AC2	–	–	–	No control valve
FC5	0.01	0.235	no stiction	nonlinear
FC6	0	–	–	linear
FC7	0	–	–	linear
FC8	0	–	–	linear
PC1	0.01	0.12	0.5	nonlinear
PC2	–	–	–	No control valve
PC3	–	–	–	No control valve
PC4	–	–	–	No control valve
PC5	–	–	–	No control valve
LC2	0	–	–	linear
LC3	0	–	–	linear
LC4	0.021	0	–	linear
LC5	0	–	–	linear
LC7	–	–	–	cascaded (FC5)
LC8	–	–	–	cascaded (FC6)
TC2	0.080	0.227	1.25	nonlinear

Table 2: Valve Stiction Diagnosis