Detection of Stiction using HOSA for a Shell and Tube Heat Exchanger Process

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ABSTRACT

Oscillations in control loops deviate the process output from desired operating value i.e. the setpoint. The presence of oscillations leads to reduced plant profitability and increased energy consumption. Oscillations in control loops may be due to various reasons. They are caused by external oscillatory disturbances, aggressive controller tuning and a very common cause for oscillations is due to nonlinearity (mostly stiction) in control valves. It is significant to detect valve stiction primarily, so that suitable action could be taken to get rid of this situation. In this paper, we mainly focus on stiction nonlinearity and to detect them using the Bispectrum and Bicoherence analysis for a highly nonlinear Shell and Tube Heat Exchanger (STHX) process.

Keywords—Oscillations, oscillating disturbances, aggressive controller tuning, valve stiction, Bispectrum, Bicoherence, STHX.

I. INTRODUCTION

Control loop performance has been significant in the past and will remain to be significant in the future. Root-causes detection of oscillations is still a problem at the current stage, with which one detects the malfunctions of a loop in many circumstances [1]. Poor control loop performance is generally the result of unnoticed deterioration in control valves and improper tuning in the controllers. Data-driven approaches to evaluate control loop performance are applied to platform with production offshore facility. The Savitzky-Golay smoothing filter, joined with a curve fitting method is used to detect stiction in control valves. A stiction index specifies whether a valve stiction has occurred [2]. The occurrence of nonlinearities in a control valve limits the performance of control loop. Stiction is the most frequently found control valve problem in process industries. Several attempts have been made to understand, model and detect stiction in control valves. The data-driven method of valve stiction [3, 4] is used with regular plant model to get the required data.

The effects of plant-wide oscillations spread to several units and influences the overall process performance. Hence it is vital to detect and diagnose the root cause of such oscillations so that the situation is rectified and profitability of the plant is maintained. Based on the nonlinearity information in the process data a new total nonlinearity Index has been defined to quantify nonlinearities [5]. To spot the root cause of oscillation from the analyzed data a concept of nonlinearity index is applied for three case studies such as valve fault, sensor fault and process nonlinearity. The nonlinearity index is large for the non-sinusoidal oscillating time trends and is sensitive to limit cycles caused by process nonlinearity and equipment [6].

Higher Order Spectral Analysis (HOSA) established over the last three decades has been widely used in the control loop monitoring. HOSA with closed-loop data diagnose the causes of poor control loop performance utilizing its tools such as cumulants, bispectrum and bicoherence to develop the non-gaussianity and the nonlinearity indices for detecting and quantifying the source of nonlinearity [7]. The application of spectral independent component analysis separates a periodical disturbance in a polyethylene plant that has a strong impact on the final variability. The causes can be due to nonlinearities in the valve, improper tuning and disturbances. By using HOSA, the source was detected and the cause was identified [8].

The proper movement of valve stem is hindered that subsequently affects the performance of control loop. It is thus essential for control engineers to understand and know the stiction phenomena so that they can deal with it and overcome them [9].This paper focuses mainly on the detection of stiction nonlinearity present in the valves of Shell and Tube Heat Exchanger process using HOSA tools such as bispectrum and bicoherence analysis.

II. VALVE STICTION MODEL

A. Structure of pneumatic control valve

Figure 1 shows the general structure of a pneumatic control valve. The valve is opened by air pressure and closed by elastic force. The position of the plug regulates the balance between elastic force and air pressure which in turn regulates the flow rate. The valve stem connected to the plug is moved against static force caused by gland packing, a device which is sealed to prevent leakage of process fluid.

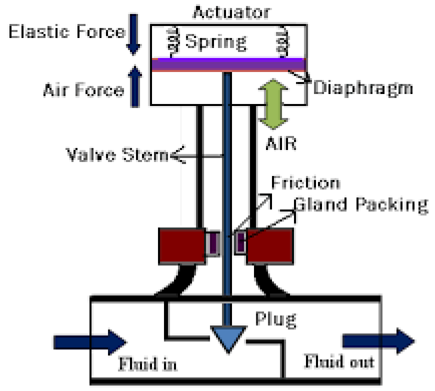

Figure 1: Structure of pneumatic control valve

B. Input-Output Characteristicof a Sticky Control Valve

Figure 2 shows the input-output characteristic of a sticky valve. The phase plot of the input–output characteristic of a control valve has stiction in it. Deadband, stickband, slip jump and the moving phase are the four components of valve stiction. When the valve comes to rest or changes the direction at point A the valve sticks. After the controller output overcomes the deadband (AB) and the stickband (BC) of the valve, the valve jumps to point D and continues to move. Due to very low or zero velocity, the valve may stick again in between points D and E while travelling in the same direction. In such a case, the magnitude of deadband is zero and only stick band is present. We can overcome this case only if the controller output signal is larger than the stickband which is usually uncommon in practice. The input to the valve keeps changing the deadband and stickband, which signifies the behavior of the valve when not moving. Slip jump represents the abrupt release of potential energy stored in the actuator chambers due to high static friction in the form of kinetic energy as the valve starts to move. Once the valve slips, it continues to move until it sticks again at point E. Dynamic friction is much lower than the static friction in the moving-phase. Slip-jump is expressed as a percentage of the output span. Stiction occurs when the smooth movement of the valve stem is hindered by excessive static friction at the packing area.

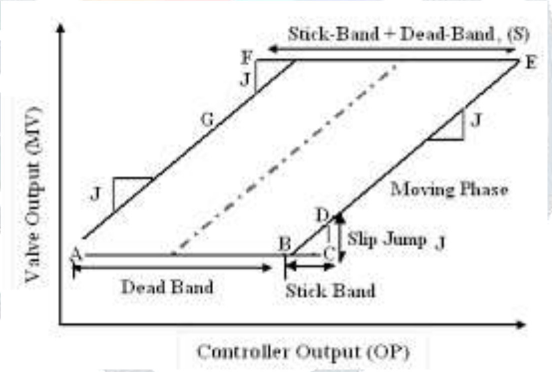

Figure 2: Input-Output Characteristic of a Control Valve with Stiction

C. **Closed loop system with valve stiction model**

Figure 3 shows the block diagram of closed loop system with the control valve stiction model. The controller chosen here is PID controller and the process taken is Shell and Tube Heat Exchanger. For Valve nonlinearity block which contains the stiction model is derived from [10].

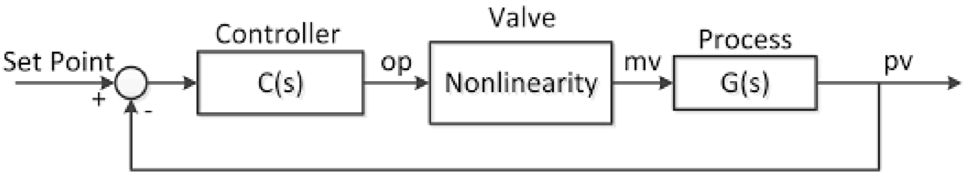

Figure3: Closed loop system with valve stiction model

III. PIPING AND INSTRUMENTATION DIAGRAM OF STHX

The Shell and Tube Heat eXchanger consists of 37 copper tubes and the length of the tubes is of 750 mm with a single pass arrangement. Here water is considered as the medium. The medium of hot and cold water can be arranged in co-current and counter-current fashion. The water in the process tank is heated to a specific operating temperature. The disturbance tank is used to study for disturbance rejection. The STHX consists of two sides namely the shell side and the tube side. The hot water runs from the process tank and enters into the tube side of STHX. Cold water is provided at room temperature and runs from the reservoir tank into the shell side of the STHX. The two power drivers regulate the voltage and current to the heaters, which in turn regulates the temperature of the water in the process and disturbance tank. Resistance Temperature Detectors are used for measuring the inlet and outlet temperatures of the hot and cold water. The Differential Pressure Transmitter is used for measuring the cold water flow rates. The pneumatic control valves are used for manipulating the cold and hot water inlet flow of the shell side and tube side fluids. The controlled variable is hot water outlet temperature whereas the manipulated variable considered here is the cold water flow rate. The process parameters are obtained from the first principles model which is simulated using MATLAB/Simulink.

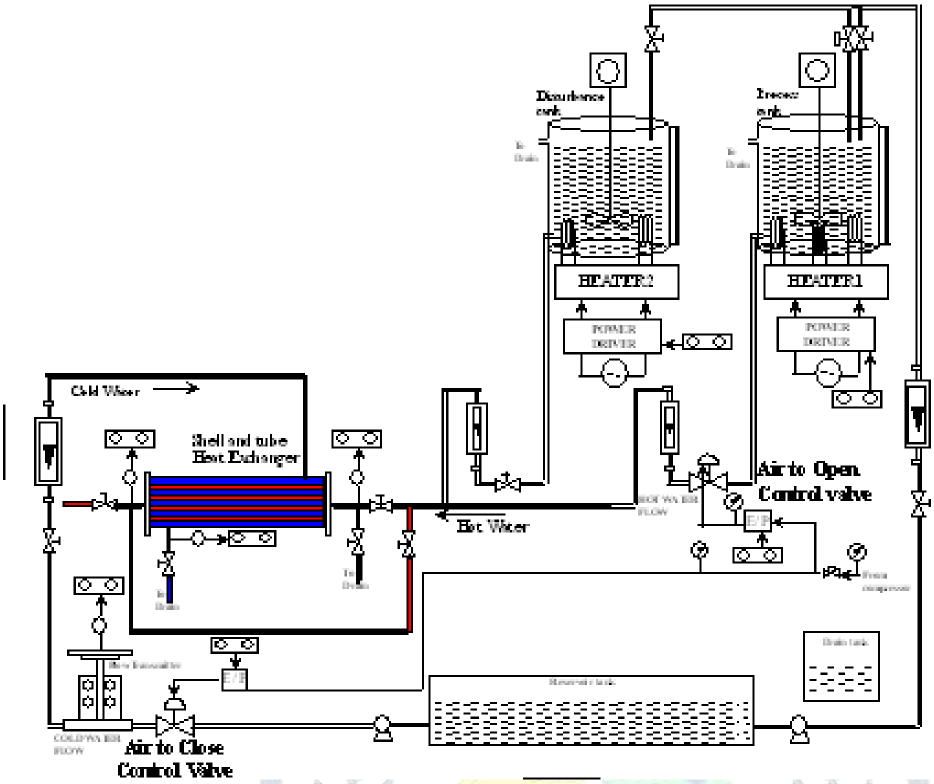

Figure 4: P & ID of STHX

IV. HOSA

Higher order spectra (HOS) also known as polyspectra is the combination of the moments and cumulants of third order and beyond them. HOS detects abnormalities from stationarity, linearity and Gaussianity in the signal. Signals which are non-linear, non-stationary and non-Gaussian are therefore more beneficial to analyze with HOS compared to the use of second-order correlations and power spectra. The Higher-Order Spectral Analysis (HOSA) Toolbox in Matlab provides complete higher-order spectral analysis capabilities for signal processing applications.

A. Bispectrum analysis

Scrutinizing the nonlinear signals in Higher Order Statistics encloses the relations between phase components. The bispectrum employs the third order cumulants and it shows the information which is not presented by the spectral domain. The bispectrum B (f1, f2) of a non-Gaussian signal, x (t), is a two-dimensional Fourier transform of the third order cumulants C (m, n) defined as:

$$C(m, n) = E[x(k)\, x(k+m)\, x(k+n)] \qquad (1)$$

Where E is the Expectation function

The bispectrum formula related to (1) is written as:

$$B(f_1, f_2) \triangleq E[X(f_1)X(f_2)X^*(f_1+f_2)] \qquad (2)$$

Where X (f) is the Fourier transform of x (t) and * represents conjugate complex. Bispectrum contains the information about the relation of phase between the frequency components at f1, f2 and f1 + f2 [11].

B. Bicoherence Analysis

Higher order spectra are the functions of two or more component frequencies unlike the power spectrum which is a function of a single frequency. A unique characteristic of a non-linear time series is the presence of phase coupling such that the phase of one frequency component is determined by the phases of others. Phase coupling leads to higher order spectral features which can be detected in the bicoherence of a signal. The nonlinearity test applied here uses bicoherence to assess the nonlinearity. Bicoherence is defined as

$$\mathrm{Bic}^2(f1, f2) \triangleq \frac{|B\,(f1,f2)|^2}{E[|X\,(f1)X\,(f2)|^2]\;E[|X\,(f1+f2)|^2]}$$

Where, B (f1, f2)is the bispectrum at frequencies (f1, f2). The bicoherence gives the same information as the bispectrum but it is normalized as a value between 0 and 1 [12].

V. RESULTS AND DISCUSSIONS

The oscillation detection method has been evaluated for SISO-STHX process using HOSA/MATLAB software. The stiction in control valve causes the process output to oscillate around the set point. The closed loop response of STHX process due to the presence of stiction in control valve has been analyzed. The SISO system is used for generating the simulated sets of data. The manipulated variable considered in the STHX process is cold water flow rate and the controlled variable is hot water outlet temperature. The first order process with time delay is given by the transfer function

$$G_p(s) = \frac{-15.5\,e^{-0.134s}}{0.773s+1} \qquad (4)$$

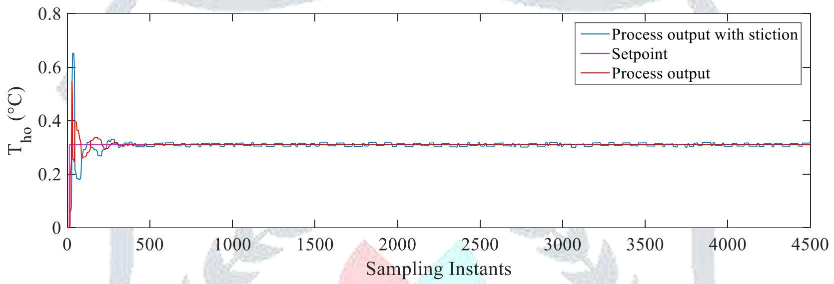

Figure 5: Response for entire operating region (With and Without Stiction)

For getting nonlinearity induced oscillatory data, a stiction model is introduced in the control loop with known values of stiction parameters. Detailed explanation of stiction model is given in [10]. Response of hot water outlet temperature in the presence of stiction is shown in fig.4. From this response simulated sets of data are collected and are given as input vector to the bispectrum analysis. Bispectrum of each signal is estimated through the direct (FFT) method. In bispectrum estimation, the FFT length is 128 and Rao-Gabr optimal window is used. The result of the bispectrum and bicoherence analysis of process output due to stiction in control valves for STHX process is shown in fig 5 and fig 6. The color variation represents the relative change in amplitude of bispectrum. The magnitude of bicoherence is bounded between 0 and 1. The higher bicoherence value indicates significant nonlinearity. From the plot, the value of frequencies (f1, f2) = (-0.28125,-0.35938). The maximum bicoherence value is found to be 0.46446. The bicoherence magnitude threshold limit for nonlinearity detection is chosen as 0.1which is chosen based on the experience of using this tool in process performance diagnosis and for this case clearly detects the stiction nonlinearity present in the process output.

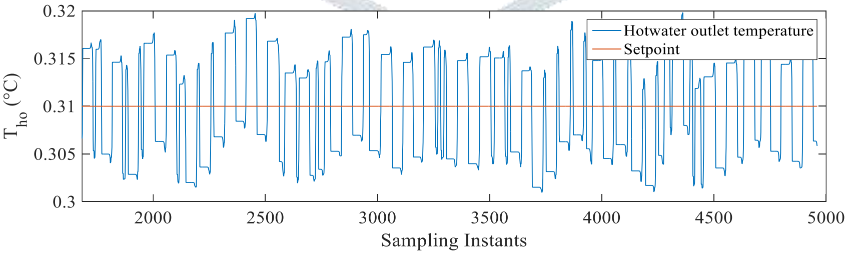

Figure 6: Response of Hot water outlet temperature (°C) in the presence of Stiction

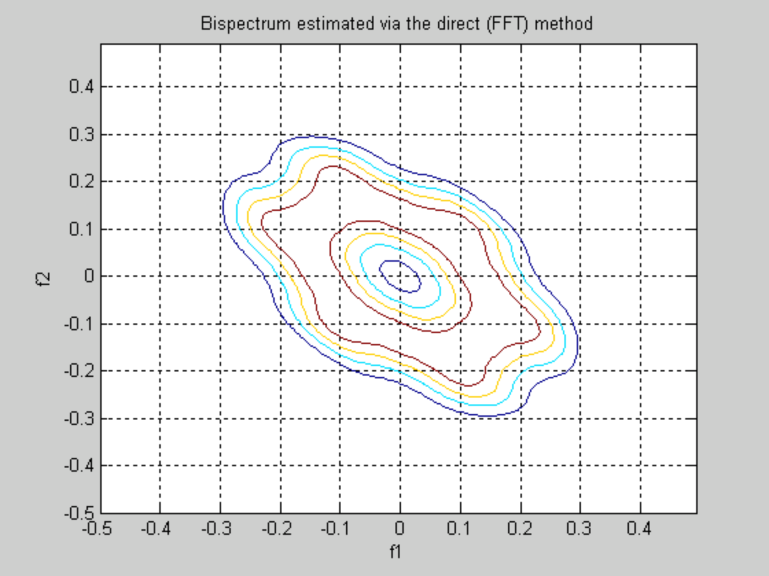

Figure 6: Bispectrum estimated due to Stiction in STHX process

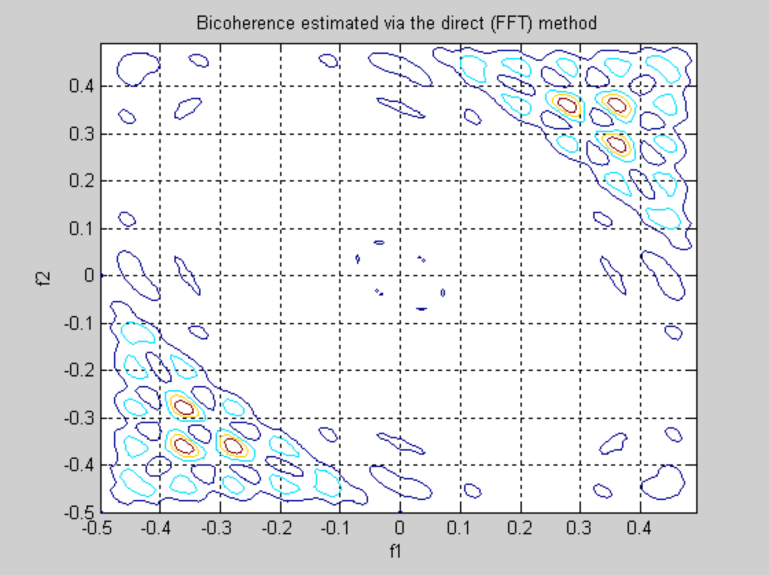

Figure 7: Bicoherence estimated due to Stiction in STHX process

CONCLUSION

This paper deals with the spectral analysis of detecting stiction in control valve for a STHX process. Higher Order Spectral Analysis techniques such as bispectrum and bicoherence are used in this paper to detect the stiction nonlinearities present in the process output. The magnitude of normalized bispectrum or bicoherence indicates the presence or absence of process nonlinearity. The future scope of this work involves some compensating techniques to overcome stiction nonlinearity present in control valves.

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