

Detection and diagnosis of Oscillation in Shell and Tube Heat Exchanger Process

S.Abirami, S.Sivagamasundari



Abstract: Oscillations found in process control loops are the visible indications of process deterioration. The presence of oscillation in an industrial control loop may reduce quality of the product; increase the rejection rate and energy consumption which may result in reduced profitability. Many techniques stated in the literature for oscillation diagnosis has their own benefits and limitations. Performance assessment of a single control loop is a valued procedure to spot suddenly rising faults and slowly emerging degradation. In this paper, the oscillations present in the process variable of a Shell and Tube Heat eXchanger (STHX) process are diagnosed using the Higher Order Spectral Analysis (HOSA) in MATLAB. From HOSA, bispectrum, modified bispectrum and bicoherence analysis technique is applied to the laboratory STHX process to spot the probable root cause for oscillations.

Keywords: Oscillation, Process performance, HOSA, MATLAB, Bispectrum, Bicoherence, Modified Bispectrum, STHX.

I. INTRODUCTION

Control performance monitoring is becoming popular in process industries. Oscillations found in process variables may be due to excessive process and measurement noise, process conditions, improper controller tuning and sometimes due to nonlinearities found in valves. Many surveys stated that an average of 30% of all loops is oscillating in process plants. The fact that certain oscillating loops are often identified, but the root causes and the suitable actions to be applied is a challenging problem. As a consequence, oscillating loops tend to be acknowledged as an unavoidable problem and so ignored or put in manual mode. The origin of oscillations is either exogenous or endogenous. Non-oscillating disturbances are described by the uneven occurrence of variations in the normal time trend, which appears as spikes or valleys. Common reasons for non-oscillating disturbances are often associated with constraints or process problems [1]. In process measurements, autocorrelation based method is used for oscillation detection. Using higher order statistical methods, signals having oscillations are evaluated for the presence of nonlinearities in control valves [2]. Automatic assessment of loop performance mainly involves the detection of control loop oscillations [3].

It is becoming increasingly significant to monitor the condition and performance of the control elements in chemical processes.

Plant time trends alone do not give a clear picture and accurate measure of a process control loop problem. An important and practical method to troubleshoot common control loop problem is introduced using signal processing and statistical techniques [4].

The presence of oscillations in process output may be result of external disturbance, improper controller tuning and control valve stiction. An effort is made to categorize oscillation, owing to occurrence of stiction non linearity found in the pneumatic control valve of a triple tank level control process [5] where the control loop performance was affected due to the occurrence of stiction. Articles [6, 7] review the improvements in detection of plant-wide disturbances, in many chemical processes and introduce new strategies. The main reasons of plant-wide oscillations include controller interactions, improper tuning and limit cycles found in control loops. The diagnosis and detection of non-linearity, specifically the effect of valve stiction, is found to be a lively zone.

The Higher-Order Spectral Analysis (HOSA) Toolbox is a group of M-files in MATLAB that implements a range of advanced signal processing algorithms. These algorithms are used for various estimations, identification and prediction process [8]. In this work, bispectrum, bicoherence and modified bispectrum analysis in HOSA is implemented to identify the root cause diagnosis for STHX process.

II. OSCILLATION DETECTION METHODS

Various oscillation detection methods from the literature are listed below. Each method has its own advantages and disadvantages [9]. To avoid false detections, Higher Order Spectral Analysis is introduced which is beneficiary in detecting and diagnosing oscillations.

A.HOSA

HOS (higher order statistics or higher order spectra), also known as polyspectra, are “spectral representations of higher order statistics, i.e. moments and cumulants of third order and beyond” [8]. There are various techniques involved in HOSA. Bispectrum, Bicoherence and modified bispectrum analysis are the techniques that are applied in this work for detection of oscillations in the STHX process.

1. Bispectrum Analysis

The relation between frequency components is significant and the bispectrum gives clear information about them whereas the power spectrum does not provide any information about the frequency components.

Revised Manuscript Received on October 30, 2019.

* Correspondence Author

S.Abirami*, Research Scholar, Department of Electronics & Instrumentation Engineering, Annamalai University, Chidambaram - 608002, India.

S.Sivagamasundari, Department of Electronics & Instrumentation Engineering, Annamalai University, Chidambaram - 608002, India.

© The Authors. Published by Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP). This is an [open access](http://creativecommons.org/licenses/by-nc-nd/4.0/) article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

To examine the nonlinear signals one among the best methods is Higher Order Statistics, as it encloses the relations between phase components. The bispectrum employs the third order cumulants and it shows the information which is not found in the spectral domain. The bispectrum $B(f_1, f_2)$ of a non-Gaussian signal, $x(t)$, is a 2-dimensional Fourier transform of the 3rd order cumulants $C(m, n)$ demarcated as:

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

Where E is the Expectation function

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

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

Where $X(f)$ is the Fourier transform of $x(t)$ and $*$ represents conjugate complex. As seen from (2), bispectrum contains the information about the relation of phase between the frequency components at f_1, f_2 and $f_1 + f_2$ [10]. Bispectrum can be estimated through several methods such as biased, parametric, direct and indirect methods. In this paper we use direct method, to compute the bispectrum of the STHX process signal [11].

2. Bicoherence Analysis

Phase coupling leads to HOS features which could be discovered by the bicoherence of a signal. Here, bicoherence is applied to evaluate the nonlinearity. Bicoherence is determined as

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

Where, $B(f_1, f_2)$ is the bispectrum at frequencies (f_1, f_2) . The bicoherence provides the same data as the bispectrum but it is normalized between 0 and 1 [12].

3. Modified Bispectrum Analysis

Equation (2) is altered for modified bispectrum analysis [13], which is used to identify the root cause for oscillations of STHX process.

$$B_M(f_1, f_2) \triangleq E[X(f_2 + f_1) X(f_2 - f_1) X(f_2) X^*(f_2) X^*(f_2)] \quad (4)$$

III. RESULTS AND DISCUSSIONS

The oscillation detection method has been evaluated for SISO-STHX process using HOSA/MATLAB software. The closed loop response of STHX process due to the occurrence of stiction phenomenon found 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

$$G_p(s) = \frac{-15.5 e^{-0.134s}}{0.773s + 1} \quad (5)$$

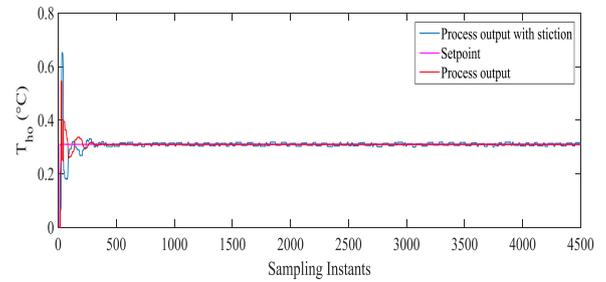


Fig. 1 Response for entire operating region (With and Without Stiction)

For getting nonlinearity induced oscillatory data, a stiction model is introduced in the process control loop with known values of stiction parameters. Response of entire operating region for with and without stiction is shown in figure 1. Response of hot water outlet temperature for 20%, 50% and 80% stiction are shown in figures 2, 3 and 4 respectively. 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 of length 128 and Rao-Gabr optimal window is used. The result of the bispectrum and bicoherence analysis of process output due to stiction problem in control valves for STHX process are shown in figures 5, 6 and 7 respectively. The color variation signifies the relative change in bispectrum amplitude. Table I gives the parameter values estimated by bicoherence. The magnitude of bicoherence varies between 0 and 1. The higher bicoherence value indicates significant nonlinearity. The bicoherence magnitude threshold limit for detection of nonlinearity is chosen as 0.1 which is based on the knowledge of using this tool in performance diagnosis and for this; it visibly identifies the stiction nonlinearity present in the process output.

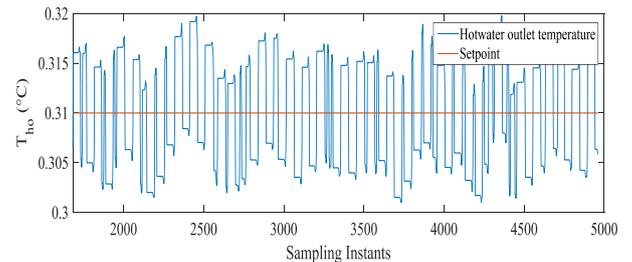


Fig. 2 Response of Hot water outlet temperature (°C) for 20% Stiction.

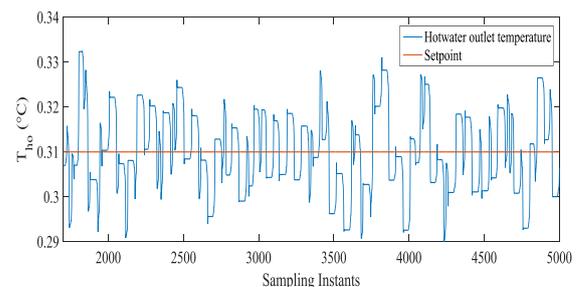


Fig. 3 Response of Hot water outlet temperature (°C) for 50% Stiction

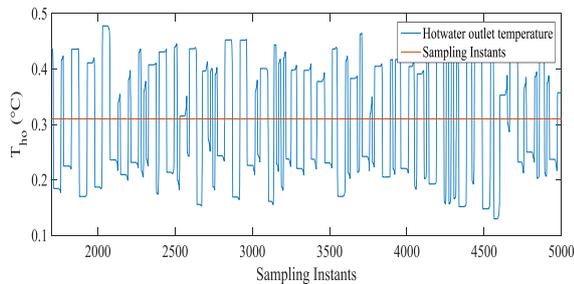


Fig. 4 Response of Hot water outlet temperature (°C) for 80% Stiction.

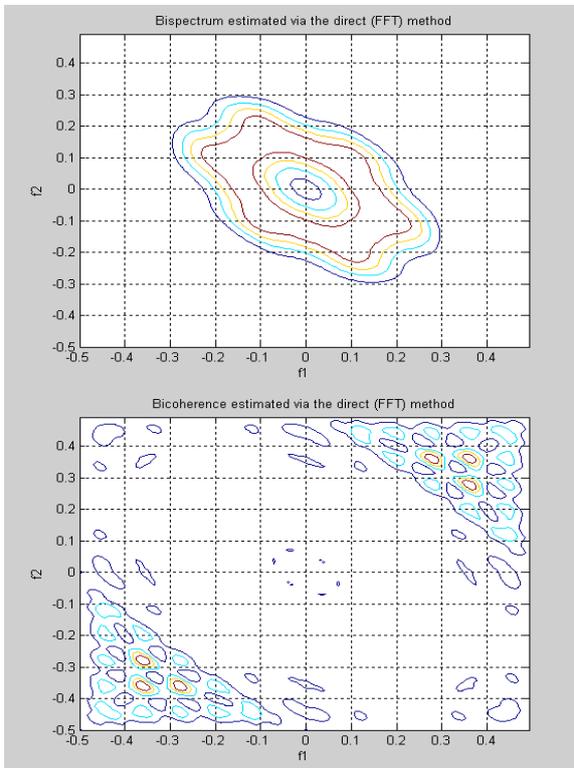


Fig. 5 Bispectrum and Bicoherence estimated due to 20% Stiction in STHX process. (From the plot, the value of frequencies (f1, f2) = (-0.28125,-0.35938). The maximum of the bicoherence value is found to be 0.46446)

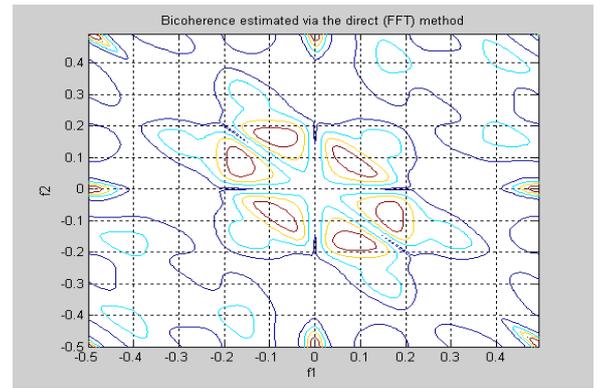
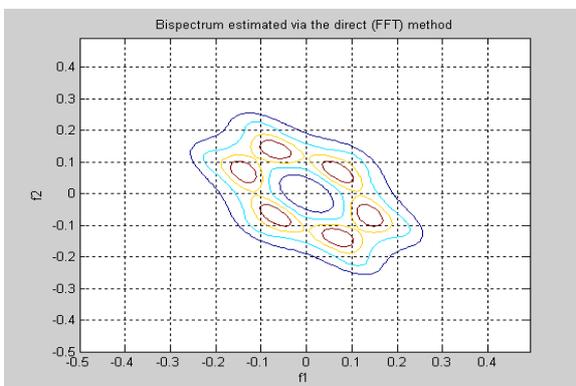


Fig. 6 Bispectrum and Bicoherence estimated due to 50% Stiction in STHX process. (From the plot, the value of frequencies (f1, f2) = (-0.5,-0.5). The maximum of the bicoherence value is found to be 0.68136)

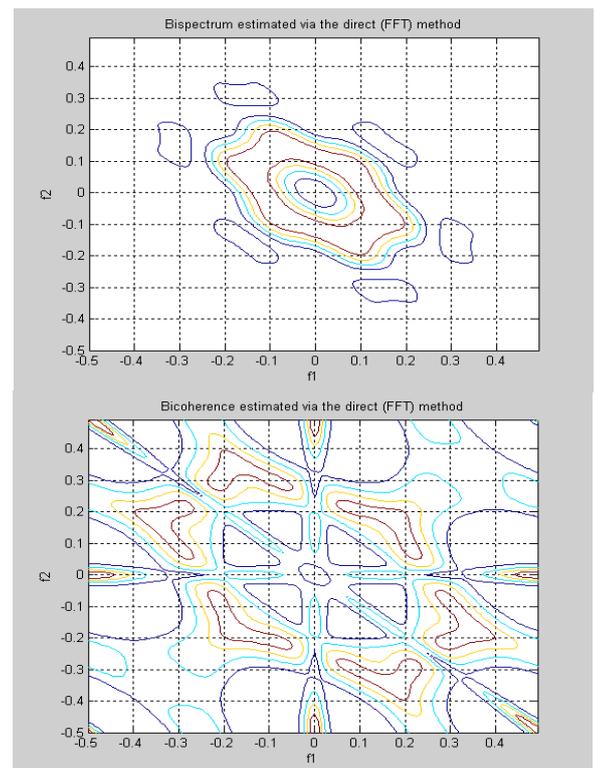


Fig. 7 Bispectrum and Bicoherence estimated due to 80% Stiction in STHX process (From the plot, the value of frequencies (f1, f2) = (-0.5,-0.5). The maximum of the bicoherence value is found to be 0.74608)

Table I. Parameter values estimated by Bicoherence

Parameters	Estimated Bicoherence
20% Stiction	0.46446.
50% Stiction	0.68136
70% Stiction	0.74608

Root causes for oscillations are not only due to valve nonlinearities (Dead band, Hysteresis, Stiction etc.) but also due to aggressive tuning and external disturbances. White noise is introduced in the closed loop to collect datasets due to external disturbance and for collection of datasets due to improper tuning changes in controller settings are made. For getting nonlinearity induced oscillatory data, a stiction model is introduced in the control loop with known values of stiction parameters. Response of hot water outlet temperature in the presence of stiction, due to external disturbance and improper tuning are displayed in fig.8, fig.9 and fig.10 respectively. From these responses simulated sets of data are collected and are given as input vector to the modified bispectrum analysis.

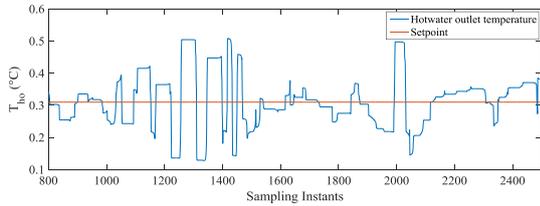


Fig.8. Oscillatory response of Hot water outlet temperature (°C) in the presence of Stiction in control valve

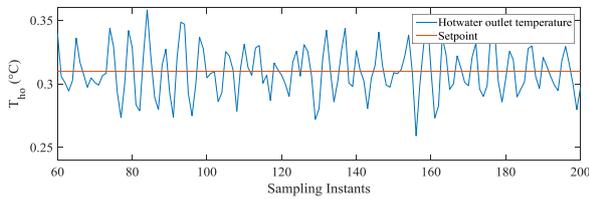


Fig.9. Response of Hot water outlet temperature (°C) in the presence of External oscillatory disturbance

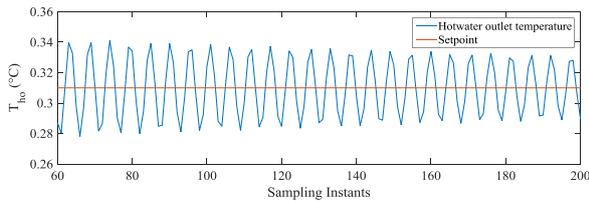


Fig.10. Oscillatory response of Hot water outlet temperature (°C) due to improper tuning

The modified bispectrum estimations of signals due to aggressive tuning are presented in Fig. 13. Fig. 11 and Fig. 12 show the results of the modified bispectrum estimations due to stiction and external disturbance. Table II shows the estimated values of modified bispectrum. The threshold value is specified to be 0.5. If the bispectrum value exceeds the threshold value nonlinearity can be confirmed. Comparing the three plots, highest bispectrum value of 0.6 is observed for the PV data which is affected by the stiction nonlinearity found in the control valve. The bispectrum values of other two oscillating process variables are found to be 0.0005 and 0.006

which are due to external disturbance and improper tuning respectively. In both situations the bispectrum is found to have multiple peaks with lesser amplitude.

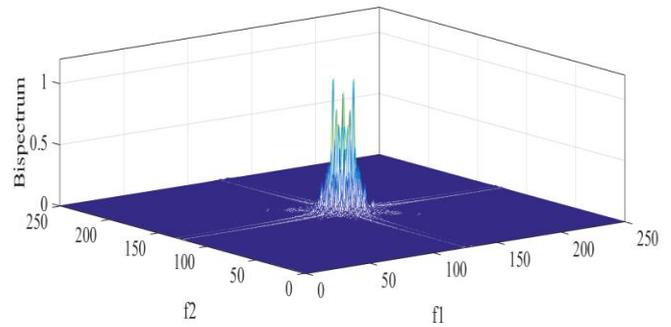


Fig.11. Modified Bispectrum of Stiction induced oscillation in STHX process variable

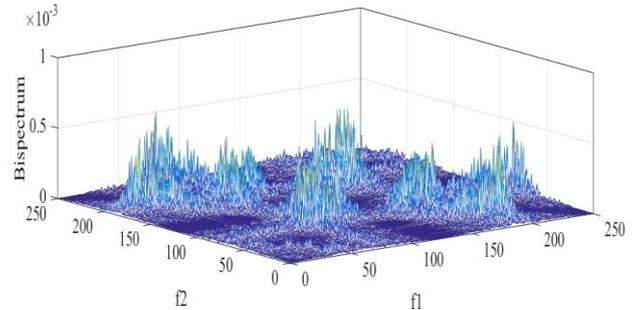


Fig.12. Modified Bispectrum of External disturbance induced oscillations in STHX process variable

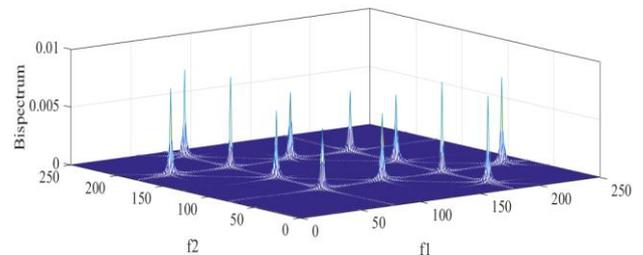


Fig.13. Modified Bispectrum of improper tuning induced oscillations in STHX process variable

Table II. Parameter values estimated due to Bispectrum

Parameters	Estimated Bispectrum
Stiction	0.6
External disturbance	0.0005
Improper tuning	0.006

IV. CONCLUSION

The main contribution of this work is to utilize HOSA tool such as bispectrum, modified bispectrum and bicoherence analysis to detect the nonlinearity present in control valves. The modified bispectral amplitude with graphical plots has been used to analyse the root causes for poor performance of control loops. The magnitude of normalized bispectrum or bicoherence indicates the presence or absence of process nonlinearity. The proposed method is demonstrated on simulated STHX process data. The results clearly shows that HOSA based modified bispectral analysis can give promising results for oscillation detection.

REFERENCES

1. Nunzio Bonavita, Jaime Caserza Bovero, Riccardo Martini and Lorenzo De Lorenzo, "Control Performance Monitoring: A Data-Driven Approach," Presented at: ANIPLA Workshop, Milan, 19 September 2006
2. M. A. A. Shoukat Choudhury, Vinay Kariwala, Nina F. Thornhill, Hisato Douke, Sirish L. Shah, Haruo Takada and J. Fraser Forbes, "Detection and Diagnosis of Plant-wide Oscillations," 16th IFAC World Congress scheduled in Prague, 2005.
3. Tore Hägglund, "Industrial Applications of Automatic Performance Monitoring Tools," 15th Triennial World Congress, Spain, 2002.
4. Ali Al-Matouq, "Plant-wide process control loop condition monitoring," Saudi Aramco Journal of Technology, pp. 52-61, 2006.
5. E. Govinda Kumar and M. Sankar, "Detection of Oscillation in Three Tank Process for Interacting and Non- Interacting Cases," IEEE, pp. 352-357, 2013.
6. Nina F. Thornhill and Alexander Horch, "Advances and New Directions in Plant-Wide Controller Performance Assessment," International Symposium on Advanced Control of Chemical Processes, Gramado, Brazil, April 2-5, pp.29-36, ADCHEM-2006.
7. Nina F. Thornhill and Alexander Horch, "Advances and new directions in Plant-Wide Disturbance Detection and Diagnosis," Control Engineering Practice, 15, 1196–1206, 2007.
8. Ananthram Swami, Jerry M. Mendel, Chrysostomos L. (Max) Nikias, "Higher-Order Spectral Analysis Toolbox User's Guide," United Signals & Systems, Inc., 1993 – 2001.
9. Peter Fogh Odgaard and Klaus Trangbaek, "Comparison of Methods for Oscillation Detection - Case Study on a Coal-Fired Power Plant".
10. Vahid Houshyarifar and Mehdi Chehel Amirani, "An approach to predict Sudden Cardiac Death (SCD) using time domain and bispectrum features from HRV signal," Bio-Medical Materials and Engineering, IOS Press, 27, pp. 275–285, 2016.
11. Ateke Goshvarpour and Atefeh Goshvarpour, "Comparison of higher order spectra in heart rate signals during two techniques of meditation: Chi and Kundalini meditation," Cogn Neurodyn – Springer, 7, pp. 39-46, 2013.
12. M.A.A. Shoukat Choudhury, S.L. Shah, N.F. Thornhill, David S. Shook, "Automatic detection and quantification of stiction in control valves," Control Engineering Practice, 14, pp. 1395–1412, 2006.
13. Abdulkarim Shaeboub, Fengshou Gu, Mark Lane, Usama Haba, Zhifei Wu & Andrew D. Ball, "Modulation signal bispectrum analysis of electric signals for the detection and diagnosis of compound faults in induction motors with sensorless drives," Systems Science & Control Engineering, 5:1, 252-267, 2017.