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An integrated approach for oscillation diagnosis in linear closed loop systems

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ABSTRACT

In industrial plants with non-oscillatory set points, oscillation detection and diagnosis are key steps to improve plant performance and safety. Oscillations in linear closed loop systems can occur due to one or more of the following reasons: (i) changes in process/controller settings, (ii) stiction in control valves, (iii) external oscillatory disturbances, (iv) quantization effects, and (v) presence of saturation and hysteresis in closed loop systems. Though there are techniques to address oscillation diagnosis problem, there are gray areas such as the identification of multiple sources that cause oscillations in the process output. In this work, this problem is addressed through the development of an algorithm to identify multiple sources of oscillations in Single Input Single Output (SISO) loops. Further, an integrated approach to diagnose both single/multiple root causes in SISO loops is presented. Simulation and industrial case studies are provided to show the applicability of the proposed algorithms.

Keywords: Oscillation diagnosis; Multiple root cause; Stiction; Interacting control loops; External disturbances

1. Introduction

Oscillation detection and diagnosis are important tasks to ensure acceptable performance of numerous control loops in industries (Huang and Shah, 1999; Choudhury et al., 2008a; Jelali and Huang, 2009; Thornhill and Horch, 2007). Further, oscillations also propagate through the process plants due to interactions among various control loops. Tight energy integration, recycle streams and heat redistribution exacerbate this problem (Thornhill et al., 2002, 2003). For instance, it is reported that about 30% of all control loops in paper mill plants were oscillating because of loop problems (Ender, 1993; Hägglund, 1995). A common cause is the presence of nonlinearity, such as control valve stiction/deadband which leads to limit cycles in a control loop (Åström, 1991; Cook, 1986; Ruel, 2000; Yang and Clarke, 1999; Torres et al., 2006). Another major cause is a marginally stable control loop due to poorly tuned controller/changes in process settings which can destabilize the system (Ordys et al., 2007; Jelali and Huang, 2009; Horch, 2000). An external disturbance is a third major reason for oscillations in control loops (Wallen, 1997; Xia, 2003).

Several methods have been developed to address the plant-wide oscillation diagnosis problem in linear closed loop systems. These approaches can be broadly classified under the following categories: (i) manual/invasive approaches such as operating the loop in manual mode (Shah et al., 2004; Gerry, 2001), (ii) multivariate techniques like spectral Principal Component Analysis (PCA) (Thornhill et al., 2002), spectral Nonnegative Matrix Factorization (NMF) (Tangirala et al., 2007), spectral Independent Component Analysis (ICA) (Xia et al., 2005), spectral envelope method (Jiang et al., 2007), transfer entropy based methods (Bauer et al., 2007) and graph theoretical approaches (Jiang et al., 2009), and (iii) univariate approaches (Horch and Isaksson, 1998; Horch, 1999; Rengaswamy et al., 2001; Choudhury et al., 2004; Srinivasan et al., 2005, 2009; Singhal and Salsbury, 2005; Ivan and

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Lakshminarayanan, 2009; Lee et al., 2008). Among the above-mentioned categories, invasive methods are not preferable as they require disturbing the plant operation. As a result, most of the recent research work has focused on both multivariate and univariate approaches. A combination of both univariate and multivariate approaches is employed to diagnose the cause for oscillations in linear closed loop systems (Thornhill and Horch, 2007; Thornhill et al., 2002).

Almost all of the existing techniques in the literature address the root cause problem by considering only two sources of oscillation in a closed loop with only one source being the cause for oscillations. Recently, a complex model identification approach has been advanced in Karra and Karim (2009) to address the root cause analysis problem in linear SISO systems by considering all three major causes for oscillations. This method estimates a disturbance model under the assumption that the disturbance corrupting the process is non-stationary. In reality, knowledge about the disturbance affecting the process is limited and therefore, it is hard to obtain a disturbance model. Recently, we proposed a root cause analysis (RCA) algorithm (Babji et al., 2012) to differentiate between all the three major causes in linear closed-loop systems under the assumption that oscillations are due to only one of them. This method uses an amplitude based discrimination algorithm using HH spectrum analysis and Hammerstein based stiction detection approach for diagnosis of root causes for oscillations.

1.1. *Contribution of this work*

Though there are several techniques for oscillation diagnosis, none of these approaches address the identification of multiple causes for oscillations in control loops. The key contribution of this article is the development of an integrated framework for oscillation diagnosis. The problem is solved by a clever integration of: (i) multiple oscillation detection algorithm (Babji and Rengaswamy, 2011), (ii) Hammerstein model based stiction detection (Srinivasan et al., 2005), and (iii) information obtained by analyzing the data-driven model obtained from Hammerstein method. Finally, an integrated approach combining the existing single root cause/proposed multiple root cause analysis algorithm is presented to address the single/multiple cause(s) for oscillations in linear SISO systems. A preliminary version of this article was presented in the ADCONIP conference (Babji et al., 2011). The root cause analysis algorithm used in that article (please see Fig. 3 in Babji et al., 2011) does not use the multiple oscillation characterization algorithm at all. As a result, a complicated approach that tightly integrates the single root cause analysis algorithm and a closed loop model analysis was proposed. A key conceptual difference in this paper is that we first view single and multiple root cause scenarios as different problems. This viewpoint with an additional assumption on the disturbance allows us to greatly simplify the multiple root causes only algorithm. This viewpoint further allows us to synthesize an integrated algorithm for single/multiple root causes that is intuitive and simple compared to the approach proposed in Babji et al. (2011). This integrated approach can be used to diagnose both single/multiple sources of oscillations in linear closed loop systems. The paper is organized as follows: Section 2 provides a summary of the existing Hammerstein based stiction detection approach along with amplitude based discrimination analysis algorithm for root cause analysis. In Section 3, the proposed multiple root cause analysis algorithm is presented. Results obtained from simulation and industrial case studies are presented in Section 4 along with an integrated algorithm for single/multiple root cause analysis in linear systems. The paper ends with some concluding remarks in Section 5.

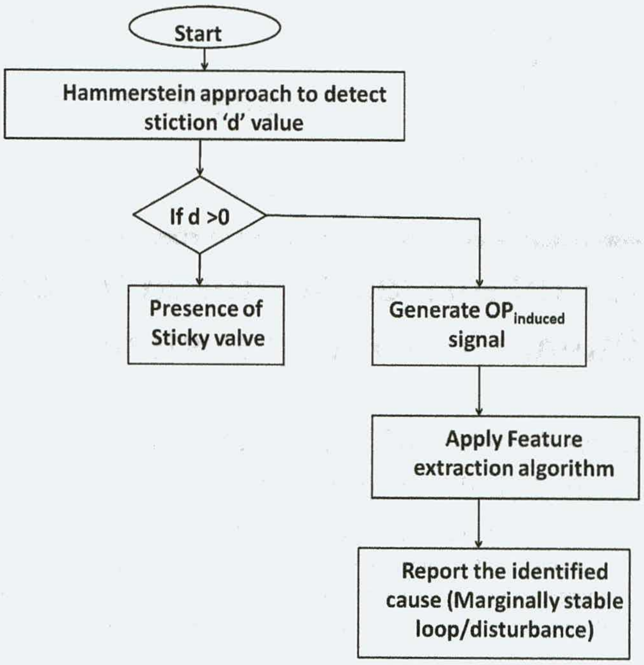

Fig. 1 – Flowchart of amplitude based discrimination analysis algorithm for identifying root cause for oscillations.

2. Preliminaries

In this section, a brief discussion on the existing Hammerstein model based stiction detection approach (Srinivasan et al., 2005) and amplitude based discrimination algorithm (Babji et al., 2012) for distinguishing between external disturbances and marginally stable control loop caused oscillations is provided.

2.1. *Brief review of Hammerstein model based stiction detection approach*

In this work, Hammerstein model-based joint identification algorithm advanced in Srinivasan et al. (2005) is used for stiction detection in control valves. This algorithm uses the following one parameter model for control valve:

$$x(t) = \begin{cases} x(t-1) & \text{if } |u(t) - x(t-1)| \le d \\ u(t) & \text{otherwise} \end{cases} \tag{1}$$

Here $x(t)$ and $x(t-1)$ represent the past and the present stem movements, $u(t)$ is the present controller output and 'd' is the valve stiction band. This approach uses a linear data driven model along with nonlinear stiction parameter to fit the data between controller output (OP) and process output (PV). The squared errors between the model predicted and process outputs are summed over a period of time to obtain the Root Mean Squared Error (RMSE). The value of stiction parameter 'd' corresponding to the model with minimum RMSE is used for stiction detection. A non-zero value of 'd' indicates stiction while a zero value implies the absence of stiction in the control valve. Currently, several variants of this algorithm