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# System identification applied to stiction quantification in industrial control loops: A comparative study[☆]

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ABSTRACT

A comparative study of different models and identification techniques applied to the quantification of valve stiction in industrial control loops is presented in this paper, with the objective of taking into account for the presence of external disturbances. A Hammerstein system is used to model the controlled process (linear block) and the sticky valve (nonlinear block): five different candidates for the linear block and two different candidates for the nonlinear block are evaluated and compared. Two of the five linear models include a nonstationary disturbance term that is estimated along with the input-to-output model, and these extended models are meant to cope with situations in which significant nonzero mean disturbances affect the collected data. The comparison of the different models and identification methods is carried out thoroughly in three steps: simulation, application to pilot plant data and application to industrial loops. In the first two cases (simulation and pilot plant) the specific source of fault (stiction with/without external disturbances) is known and hence a validation of each candidate can be carried out more easily. Nonetheless, each fault case considered in the previous two steps has been found in the application to a large number of datasets collected from industrial loops, and hence the merits and limitations of each candidate have been confirmed. As a result of this study, extended models are proved to be effective when large, time varying disturbances affect the system, whereas conventional (stationary) noise models are more effective elsewhere.

## 1. Introduction

Oscillations in control loops cause many issues which can disrupt the normal plant operation. Typically fluctuations increase variability in product quality, accelerate equipment wear, move operating conditions away from optimality, and generally they cause excessive or unnecessary energy and raw materials consumption. The common sources for oscillatory control loops can be found in poor design of the process and of the control system, e.g. choice and pairing of controlled and manipulated variables, from one hand. From another hand, poor controller tuning, oscillatory external disturbances, and control valve nonlinearities such as stiction, backlash and saturation, are frequent causes of excessive loop oscillations. Therefore, control loop monitoring and assessment methods are recognized as important means to improve profitability of industrial plants. An effective monitoring system should, first of all, detect loops with poor performance. Then, for each faulty loop, it should indicate the sources of malfunction (among possible causes) and suggest the most appropriate way of correction.

Among actuator problems, valve stiction is said to be the most common cause of performance degradation in industrial loops [2]. An extensive characterization of this phenomenon was firstly given in [3]. Two kinds of models are commonly used to describe stiction: models derived from physical principles and models derived from process data. Physical models are more accurate, but owing to the large number of unknown parameters, they may not be convenient for practical purposes [4,5]. This is the main reason why data-driven models are typically preferred [3,6–9].

A review of a significant number of stiction detection techniques recently presented in the literature is reported in [2]; among them: cross-correlation function-based [10], waveform shape-based [7,11–14,8,15], nonlinearity detection-based [16], and model-based algorithms [17]. In [2] a comparison of performance is also presented by applications on a large benchmark (93 loops) of industrial data.

Following their conclusions, research on stiction *modeling* and *detection* (i.e. confirmation of its presence) has to be considered a mature topic, even if it may happen that different results are

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[☆] A preliminary version of this paper has been presented in Bacci di Capaci et al. [1].

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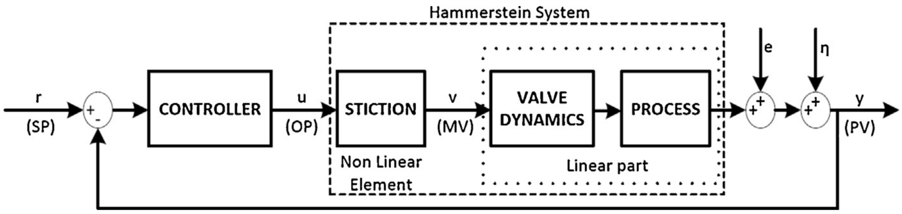

**Fig. 1.** Hammerstein system representing the (sticky) control valve followed by the linear process, inserted into the closed-loop system.

obtained once applied on the same industrial dataset, owing to complexity and superposition of different phenomena. Stiction *quantification* instead has to be regarded as an area where research contributions are still needed. The main difficulty in quantifying the amount of stiction arises from the fact that the valve stem position (MV) is not measured and recorded in many (old designed) industrial control systems [18], and then it must be reconstructed from available measurements (controlled variable, PV, and controller output, OP) by using a data driven stiction model.

In stiction quantification techniques, the control loop is often modeled by a Hammerstein system: a nonlinear block for valve stiction, followed by a linear block for the process. This approach was firstly used in [19] along with a one parameter stiction model given in [6]. However this method may not capture the true stiction behavior since the nonlinear model is not always very accurate. Subsequently, other techniques have been proposed [20–23]. A specific linear model was used in [17], which also accounts for nonstationary disturbances entering the process. The control loop was modeled as a Hammerstein-Wiener structure also in [24]. More recently, a technique based on harmonic balance method and describing function identification was proposed in [25]. A simplified method based on a new semi-physical valve stiction model was illustrated in [26].

A recent paper by the authors [18] pointed out that, while simulation is the first necessary step to check mathematical consistency of a proposed identification technique, its validation on a single set of industrial data can be pointless due to the superposition of unknown effects, such as nonstationary disturbances. As a confirmation, results obtained by different quantification techniques can be very inconsistent once applied on the same set of industrial data (as it happened in benchmark presented by [2, Chap. 13]). To overcome this problem, it is suggested in [18] to repeat stiction estimation for different data acquisitions for the same valve, in order to follow the time evolution of the phenomenon and to disregard anomalous cases (outliers). The comparison of reasonable values of stiction with predefined acceptable thresholds allows one to schedule valve maintenance in a reliable way (on-line stiction compensation is also an alternative, though not very popular in industry).

Following the above considerations, this paper represents a continuation of the work reported in [18], and addresses the following new objectives: (i) to compare some different identification techniques (of the linear model in the Hammerstein system) when applied on the same dataset; (ii) to show how external nonstationary disturbances can influence stiction estimation and system identification. Both aspects were not considered in the methodology presented in [18] where a single (ARX) model structure and a single identification technique were considered, and nonstationary disturbances were not modeled. Preliminary results of this study were reported in [1].[1]

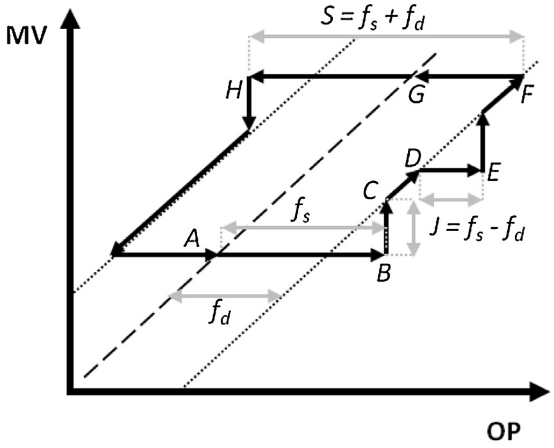

**Fig. 2.** Valve stiction: theoretical behavior of MV vs. OP, and graphical representation of Kano's and He's model parameters.

The remainder of this paper is organized as follows. In Section 2, five different models and identification methods of the linear block (in the Hammerstein system) and two models for the stiction nonlinearity are illustrated. The merits of each model and identification method are firstly assessed in simulation in Section 3, and then validated in a pilot plant in Section 4. Section 5 is dedicated to applying and evaluating the different techniques to several industrial data sets. Finally, conclusions are drawn in Section 6.

## 2. Hammerstein system: models and identification method

In this work, the control loop is modeled by a Hammerstein system as depicted in Fig. 1. Two well-established stiction models are used to describe the nonlinear valve dynamics: Kano's [7] and He's [8] model. Five different models describe the linear process dynamics: ARX (Auto Regressive model with eXternal input), ARMAX (Auto Regressive Moving Average with eXternal input), SS (State Space model), EARX (Extended Auto Regressive model with eXternal input), EARMAX (Extended Auto Regressive Moving Average with eXternal input [27]).

### 2.1. Nonlinear stiction models

In Kano's stiction model [7], the relation between the controller output (the desired valve position) OP and the actual valve position MV is described in three phases (Fig. 2):

I. *Sticking*: MV is steady (*A*–*B*) and the valve does not move, due to static friction force (dead-band + stick-band, *S*).
II. *Jump*: MV changes abruptly (*B*–*C*) because the active force unblocks the valve, which jumps of an amount *J*.

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[1] The present paper extends these previous results in an application-oriented direction. Different simulation examples and new datasets of pilot plant are now illustrated, and, mostly, results obtained from several registrations of industrial control loops are shown.