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Data-based automated diagnosis and iterative retuning of proportional-integral (PI) controllers

Tim Spinner [a], Babji Srinivasan [b], Raghunathan Rengaswamy [a,c,*]

[a] Department of Chemical Engineering, Texas Tech University, Lubbock, TX 79409, United States
[b] Department of Chemical Engineering IIT Gandhinagar, Ahmedabad 382525, India
[c] Department of Chemical Engineering, IIT Madras, Chennai 600036, India

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ABSTRACT

This work presents a new look at the existing data-based and non-intrusive PI (proportional-integral) controller tuning assessment methods for SISO (single-input single-output) systems under regulatory control. Poorly tuned controllers are a major contributor to performance deterioration in process industries both directly and indirectly, as in the case of actuator cycling and eventual failure due to aggressive tuning. In this paper, an extensive review and classification of performance assessment and automated retuning algorithms, both classical and recent is provided. A subset of more recent algorithms that rely upon classification of poor tuning into the general categories of sluggish tuning and aggressive tuning are compared by their diagnostic performance. The Hurst exponent is introduced as a method for diagnosis of sluggish and aggressive control loop tuning. Also, a framework for more rigorous definitions than previously available of the terms "sluggish tuning" and "aggressive tuning" are provided herein. The performance of several tuning diagnosis methods are compared, and new algorithms for using these tuning diagnosis methods for iterative retuning of PI controllers are proposed and investigated using simulation studies. The results of these latter studies highlight the possible problem of loop instability when retuning based upon the diagnoses provided by data-based measures.

1. Introduction

The typical process control engineer is responsible for several hundred or more loops. They must split their time between implementing new assets and maintaining existing controllers (Desborough & Miller, 2001). Perhaps as a result, surveys report that more than 60% of controllers provide less than acceptable levels of performance, leading to poor product quality and loss of production (Desborough & Miller, 2001; Bialkowski, 1993; Ender, 1993). These industrial surveys indicate that at least 30% of control loops were increasing the variability of the process variable compared to the use of manual control, and another 36% of processes were in open loop. Among the major causes exists poor controller tuning, with sometimes one quarter of all loops never adjusted from the default controller parameters (Ender, 1993). Lack of manpower and lack of tuning knowledge, combined with the time varying nature of process and disturbance behaviors (Chia & Irving, 2003) make the disappointing results unsurprising. The field of closed-loop performance monitoring and diagnosis (CLPM&D) seeks to provide tools to aid plant personnel in identifying poorly performing loops and suggesting remedial action, which may include controller retuning.

CLPM&D is a maturing area with several excellent articles (Harris, Seppala, & Desborough, 1999; Jelali, 2006; Qin, 1998; Joe Qin & Yu, 2007; Shardt et al. 2012) and books (Huang & Shah, 1999; Jelali, 2013; Ordys, Uduehi, & Johnson, 2007) providing a general overview, with additional monographs available on more specialized topics such as valve stiction detection and diagnosis (Choudhury, Shah, Thornhill, & Shook , 2006; Jelali & Huang, 2010). Some of the major causes for poor control loop performance that CLPM&D techniques attempt to identify include oscillatory disturbances (Babji, Nallasivam, & Rengaswamy, 2012), sensor or actuator faults (such as in the case of valve stiction), or poor controller tuning. Interest in the field of CLPM&D has increased dramatically following the appearance of Harris's (1989) paper (Harris, 1989) on the minimum variance benchmarking of loop performance. Comparing against the theoretical minimum variance of the process variable provides control engineers a way to quantitatively assess the current performance of each loop. Since the original minimum variance benchmark only considered the performance limiting effects of time delay, subsequent works sought to include other limitations on loop performance such as interactions in multivariate systems (Huang, Shah, & Kwok, 1995; Harris, Boudreau, & MacGregor, 1996), right half plane zeros (Tyler

* Corresponding author. Tel.: +91 806 742 1765; fax: +91 806 742 3552.
E-mail address: raghu.rengasamy@ttu.edu (R. Rengaswamy).

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& Morari, 1995), but especially the effects of restricted controller structure (Grimble, 2002). Notably, several methods exist wherein process and disturbance model information for a given system is used in an attempt to define an upper bound on performance achievable by PI or PID control (Ko & Edgar, 1998, 2004; Sendjaja & Kariwala, 2009).

PID is the dominant controller algorithm within the process industries, with one survey reporting that 97% of controllers were of this type (Desborough & Miller, 2001), while other references reporting that the actual implementation of these controllers is usually in PI form (Visioli, 2005; Åström, 1995). Although the seminal work of Ziegler and Nichols occurred over 70 years ago (Ziegler & Nichols, 1942), research in the field of PID control is still experiencing a rapid growth in the number of publications (Wang, Ye, Cai, & Hang, 2008), and a volume by O'Dwyer contains over 400 tuning correlations for PID controllers (O'Dwyer, 2006). Still, proper tuning of these controllers for optimal performance is not always a priority that the responsible engineer has time for. Often these PI controllers are retuned only in the case that oscillations have been detected and thus remain sluggishly tuned otherwise due to lack of manpower or expertise (Hägglund, 1999). Tuning in times of minimal disturbance can result in loops unable to properly attenuate common disturbances properly. Retuning is also necessary due to process changes or changes in operating regimes. Instrument wear and equipment fouling (e.g. Matsumura, Ogata, Fujii, & Shioya, 1998) cause the process dynamics to drift and time delays to increase. When applying PI or PID control to nonlinear processes, a change in operating regime should be an impetus for parameter retuning. Controller or process parameter changes within interacting loops will also necessitate retuning. All of these scenarios indicate a need for CLPM&D techniques to identify problematic loops in need of retuning.

Long before the formal advent of the CLPM&D field, there has existed a wide assortment of automated methods to assess and correct poor controller tuning, these belonging to the fields of automatic tuning and adaptive control (Åström & Wittenmark, 1994; Isermann, Matko, & Lachmann, 1992). In fact, it is likely that many of the techniques discussed throughout this work were present in industry long before being documented in the literature. It is proposed that these existing methods should be able to achieve improved outcomes if combined with other CLPM&D techniques. For example, many adaptive tuning methods would identify excessive oscillations as being associated with aggressive controller tuning (Seem, 2006), when in fact they could be present for a variety of reasons such as valve or sensor degradation other sources of hysteresis within the loop, or externally induced, oscillations beyond the capablity of the loop to compensate. This is why it is recommended (Jelali, 2006) to attempt detection of other specific types of malfunctions, for example by applying nonlinearity indices (Choudhury, Shah, & Thornhill, 2004) or Hammerstein stiction detection methods (Srinivasan, Rengaswamy, Narasimhan, & Miller, 2005), before assigning poor loop performance to controller tuning. In this way, controller tuning will not be inadvertently worsened when other problems are afflicting the loop.

Closed-loop performance monitoring and diagnosis based PI/PID tuning assessment techniques and the previously existing data-based automated tuning methods can be classified in a similar way. In one category, a model of the open loop process and possibly a model of the disturbance filter are used to calculate an upper bound on performance, referred to as PI or PID achievable performance, and then the current performance is judged against this benchmark. As a result of the parameter optimization used to predict the best achievable performance, the optimal controller tunings are also acquired. However, the requirement of model information by these assessment techniques is not easily achieved. Process models are available for only a small minority of control loops (Desborough & Miller, 2001). Therefore, use of model-based techniques produces the need for either identification experiments or else the existence of specific conditions (excitation by set point changes) that may not be present in most loops. Thus the model information dependent techniques may be severely limited in applicability. Other types of PI/PID controller assessment and retuning require only operating data that includes responses to either step-type or stochastic disturbances, in order to diagnose and/or correct tuning problems. The comparative disadvantage of this type of assessment technique is that they cannot produce knowledge of the distance from the optimal set of tuning parameters, so that retuning with these techniques requires an iterative approach towards acceptable performance. However, the largest advantage of these data-based methods is that they can be implemented without the expense and intrusion of plant identification experiments.

1.1. Contributions of this work

Data-based techniques for controller tuning assessment and correction have an important role to play in increasing process plant performance. This work presents review and discussion of several aspects concerning data-based diagnosis and retuning and new ideas and improvements to existing techniques are proposed. It should be noted that Jelali (2013) gives a comprehensive overview of a wide range of topics within the CLPM&D framework and especially that chap. 14 of Jelali (2013) includes the basis of several techniques improved by this work. In the following, we present

(1) A new categorization of the multitude of available loop tuning assessment and retuning techniques is proposed (Section 2).
(2) A subset of the tuning assessment techniques is selected, concentrating on several diagnosis measures which categorize poor controller tuning as either sluggish or aggressive. First a description of each of the selected diagnosis measures is provided (Section 3).
(3) A novel use of the Hurst exponent as an additional tuning diagnosis measure will also be explored. Section 4 provides details of this schema.
(4) Several definitions of the classifications "sluggish" and "aggressive" are examined, and a rigorous definition of these terms is proposed (Section 5).
(5) Comparison studies rate the selected diagnosis measures based upon correct classification of PI controller parameters sets into the newly defined sluggish and aggressive categories. The diagnosis measures are calculated upon the responses of systems subjected to a step in load disturbance magnitude (Section 6).
(6) Finally, use of the selected diagnosis measures within an iterative retuning algorithm is explored (Section 7).

Throughout, issues with and limitations of the use of data-based techniques are highlighted. The problem of stability during retuning and the insufficiency of current and proposed techniques in this regard are stressed.

2. Classification of tuning assessment and retuning techniques

The idea of using automated performance monitoring and adaptive tuning of PID controller parameters has existed for many years. By 1950, Caldwell (1950) had proposed an intricate mechanical design for adjusting the tuning knobs of a PID controller in order to reach Ziegler–Nichols (Ziegler & Nichols, 1942) type tuning. In Caldwell's design, the integral and derivative gains were adjusted to be a set proportion and inverse proportion,