Journal of the Taiwan Institute of Chemical Engineers 000 (2018) 1–17

Contents lists available at ScienceDirect

Journal of the Taiwan Institute of Chemical Engineers

journal homepage: www.elsevier.com/locate/jtice

Performance assessment of control loops involving unstable systems for set point tracking and disturbance rejection

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ARTICLE INFO

Article history:
Received 26 September 2017
Revised 12 January 2018
Accepted 17 January 2018
Available online xxx

Keywords:
PID controller
Unstable systems
Performance assessment
IAE

ABSTRACT

In this article, a performance assessment method that measures the performances of set point tracking as well as disturbance rejection characteristics of PID controllers designed for unstable processes is proposed. The lower bounds of integral absolute errors (IAE_o) are derived from the desired closed loop transfer function subjected to set point changes which may be of step or ramp types. The performance index is developed by considering Direct Synthesis (DS) method for PID controller design. Based on the theoretical bound IAE_0, a dimensionless index is elucidated as the ratio between IAE_0 and the actual IAE obtained from closed loop response under step set point changes and load variable changes. Considering this IAE based index as the performance measure of PI/PID control loops, the effectiveness of the controller is evaluated and tested on different types of unstable first order or second order plus time delay processes. Simulation studies for both set-point changes and disturbance rejection on various numerical examples are performed to prove the validity of the suggested performance benchmark.

1. Introduction

As more than 95% of process industries utilize PI/PID controllers, the tuning of these controllers have become one of the key factors to deal with performance problems, large process uncertainties, unstable control loops [1]. Improper PID settings for unstable systems with time delays lead to oscillatory or aggressive loop responses, poor load disturbance rejection and even low level of robustness [2]. If these drawbacks were rectified, the quality of the products gets enhanced along with the safety factors. Stability analysis and design of different types of control systems for unstable systems has been carried out by many researchers in the literature. Sree and Chidambaram [2] presented the existence and control of unstable processes. Silva et al. [3] presented new results on the stability ranges of PID controllers for stable and unstable first order time delay systems using Hermite-Biehler theorem. Gu and Niculescu [4] reviewed the techniques for stabilization for stable time delay systems. Huang and Huang [5] derived analytical expressions for describing the stability domain boundaries using D-partition technique for first order unstable systems. Michiels and Niculescu [6] discussed different stability methodologies using Eigenvalue based approaches for time delayed systems. Recently, Seer and Nandong [7] proposed stabilization and PID tuning algorithms for second order unstable systems. All these stability analysis methods provide improved understanding on the existence of a stabilizing range of each PID parameter.

Many control design methodologies are developed for unstable time delay processes [8,9]. Liu et al. [10] developed two-degrees of freedom control scheme for time delayed unstable processes with more than one controller. Shamsuzzoha and Lee proposed a control scheme for enhanced disturbance rejection [11]. Chen et al. [12] have developed set point weighted PID controller tuning for time delayed unstable systems. Based on the set point weighting parameter, they used a simple PID-PD controller to achieve basic and modified PID structures. Panda [13] synthesized PID controller using Laurent's series approximation based approach for different types of unstable and integrating processes and obtained improved performances. Nasution et al. [14] developed set point weighted controller using optimal H_2-IMC method. Vanavil et al. [15] designed PID controllers using direct synthesis method and maximum sensitivity. Nandong and Zang [16] developed high performance multi scale control scheme and showed improved performance over many methods. The plant is decomposed in to sum of basic factors where an individual sub controller is specifically designed to control each factor. An overall controller is then synthesized via combining all the sub-controllers in a manner to achieve good cooperation among the entire plant modes. They developed a new approach of control system design to achieve

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https://doi.org/10.1016/j.jtice.2018.01.024
1876-1070/

enhanced closed loop performances. Vanavil et al. [17] developed analytical tuning rules based on IMC method and H_2 minimization theory. Cho et al. [18] derived simple analytical equations for PID controller based on direct synthesis method. Recently, direct synthesis based approach [19] and dominant pole placement approach [20] are proposed for controller design for unstable systems. Apart from these techniques, there are also methods developed based on heuristic algorithms/soft computing techniques. The heuristic algorithms/soft computing assisted PI/PID tuning rules for unstable systems has advantages viz. they are non-model based, can be applied for higher order systems without model reduction. However, the limitations of these techniques are they are computationally heavy, leading to increased computational burden and convergence to the optimal solution cannot be guaranteed.

It can be understood from the above literature that there are many developments for controller design, stability analysis for unstable systems. However, the performance assessment techniques for unstable systems are limited. The performance assessment of a control loop aims at evaluating how well a control target is achieved by tuning the control loop. This assessment is carried out to identify whether the controller is able to provide relevant outputs to track the set point and rejects the load disturbance. Hence, a standard methodology is needed to analyse whether the developed control scheme could meet concurrently the contradictory performance requirements on set point tracking and load disturbance rejection. Thus, PID control loop performance for unstable models needs to be evaluated, which significantly plays a role in industries. To reach this objective, a benchmark has to be derived based on which the performance of the control loop can be calculated. Harris [21] introduced a well-known minimum variance control (MVC) benchmark with which the control loop performance was assessed. Huang and Shah [22] discussed several methods and principles of performance assessment to assess the load disturbance rejection performance. To analyse the proper tuning of control loops, Hagglund [23] suggested an idle index. MVC benchmark is not achievable if the controller structures are confined to PID form. Hence, to estimate the feasible minimum variance bound for PID controllers, Jain and Lakshminarayanan [24], Ko and Edgar [25,26] and Sendjaja and Kariwala [27] took efforts to work on the above mentioned benchmark. Huang [28], Horton et al. [29] and Grimble [30], studied the LQG cost function and developed a benchmark by considering the constraints imposed by PI/PID controllers. By proposing the area and the idle index, Kuehl and Horch [31] and Visioli [32], evaluated the PID control loop performance in the presence of disturbances.

Efforts have been put forth by many researchers to develop the index based on IAE. Swanda and Seborg [33] and Huang and Jeng [34] took the same idea and estimated the lower bound of IAE based on the step responses for PI/PID control loops. Yu et al. [35] established the theoretical bound of IAE to assess the performance of controllers for set point changes. Yu and Wang [36] developed a measure for performance assessment for input load disturbance rejection. Later, Yu et al. [37] developed IAE based index for both set point changes and load disturbance rejection. Based on the SIMC tuning rule, Veronesi and Visioli [38,39] presented two IAE based indices for PID controllers developed from closed loop responses subjected to step changes. Veronesi and Visioli [40] assessed the performance of controller for integral processes. All these works are focused either for stable processes or integrating processes. Research related to performance assessment of PID control loops for unstable processes is limited. Tyler and Morari [41] presented a data analysis tool that was applied to unstable and non-minimum phase (NMP) systems. Having this as the motivation, the proposed work focuses on the performance evaluation of PID control loops for unstable systems for set point changes and also for disturbance rejection.

The present control loop performance assessment method uses the PI/PID controller design using direct synthesis rule developed by Cho et al. [18]. The theoretical bounds of IAEs based on the direct synthesis method from closed loop responses subject to step and ramp types of set point changes are established. By using the subordinate bounds of the IAE as a benchmark, a DS-IAE based index is developed to assess the set point tracking performance and load disturbance rejection of PI/PID control loops. The current PI/PID control loop performance is near to the ideal one only when the proposed index is close to one. This manuscript is structured as follows. Section 2 briefly reviews the direct synthesis tuning scheme. The lower bound of the IAE based on the direct synthesis method for UFOPDT (unstable first order plus dead time) process, is discussed in Section 3. Section 4 proposes the lower bound of the IAE for USOPDT (unstable second order plus dead time) system. Section 5 illustrates a DS-IAE based performance index. Section 6 presents several examples, correspondingly, to check the performance benchmark, and to demonstrate the efficacy of the proposed performance index. Section 7 ends with the concluding remarks.

2. PI/PID controller design

Consider a SISO (single input and single output) process where the poles are in right half of 's' plane. For such processes, two degree of freedom controllers are required for better responses of both set-point and load changes. The PID control system $C(s)$ with the set-point filter $F_r(s)$ is considered as shown in Fig. 1.

Here, $G(s)$ is the process, $C(s)$ is the controller, $R(t)$, $R'(t)$, are the set points, $D(t)$, $U(t)$, $E(t)$ and $Y(t)$ are the disturbance, control variable, error and process variable. $G(s)$ is confined to be a process which is either unstable first order plus dead time model,

$$G(s) = \frac{k_p e^{-\theta s}}{\tau s - 1} \tag{1}$$

or second order plus dead time model with one or two unstable poles,

$$G(s) = \frac{k_p e^{-\theta s}}{(\tau_1 s - 1)(\tau_2 s - 1)} \tag{2a}$$

$$G(s) = \frac{k_p e^{-\theta s}}{(\tau_1 s - 1)(\tau_2 s + 1)} \tag{2b}$$

where the poles are real and distinct. Here, k_p is the process gain, τ, τ_1,τ_2 are the time constants, θ is the dead time. Eqs. (2a) and (2b) can be written in a general form as

$$G(s) = \frac{k_m e^{-\theta s}}{s^2 + \tau_{p1} s + \tau_{p0}} \tag{2c}$$

For controlling this kind of processes, the PID controller C(s) takes the parallel form

$$C(s) = k_c\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \tag{3}$$

where k_c is the proportional gain, τ_i is the integral time and τ_d is the derivative time. The controller settings based on the direct synthesis based method designed by Cho et al. [18] for UFOPTD model are given as:

$$k_c = \frac{\beta\tau}{k_p\left(\lambda^2 + \beta\theta\right)}; \qquad \tau_i = \beta; \qquad \tau_d = 0 \tag{4a}$$

where $\beta = \frac{2\lambda\tau + \theta\tau + \lambda^2}{\tau - \theta}$ and λ is the tuning parameter and the controller settings for USOPTD model are:

$$k_c = \frac{\beta_1}{k_m\left(\lambda^3 + \beta_2\theta\right)}; \ \tau_i = \beta_1; \ \tau_d = \frac{\beta_2}{\beta_1} \tag{4b}$$

Please cite this article as: Ghousiya Begum K et al., Performance assessment of control loops involving unstable systems for set point tracking and disturbance rejection, Journal of the Taiwan Institute of Chemical Engineers (2018), https://doi.org/10.1016/j.jtice.2018.01.024