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Research Article

PID controller auto-tuning based on process step response and damping optimum criterion

Danijel Pavković [a,*], Siniša Polak [b], Davor Zorc [a,1]

[a] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, I. Lučića 5, HR-10000 Zagreb, Croatia
[b] INA-Oil Industry d.d. – Sisak Oil Refinery, Ante Kovačića 1, HR-44000 Sisak, Croatia

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ABSTRACT

This paper presents a novel method of PID controller tuning suitable for higher-order aperiodic processes and aimed at step response-based auto-tuning applications. The PID controller tuning is based on the identification of so-called n-th order lag (PTn) process model and application of damping optimum criterion, thus facilitating straightforward algebraic rules for the adjustment of both the closed-loop response speed and damping. The PTn model identification is based on the process step response, wherein the PTn model parameters are evaluated in a novel manner from the process step response equivalent dead-time and lag time constant. The effectiveness of the proposed PTn model parameter estimation procedure and the related damping optimum-based PID controller auto-tuning have been verified by means of extensive computer simulations.

1. Introduction

Many industrial processes such as heat and fluid flow processes are characterized by slow aperiodic dynamics (lag behavior) and dead-time (transport delay), which are frequently modeled by a control-oriented first-order plus dead-time (FOPDT) process model [1,2], and are in a majority of cases still controlled by Proportional-Integral-Derivative (PID) controllers [3–5]. Accordingly, the PID controller auto-tuning still remains an interesting and propulsive R&D field (see [6] and references therein), which has resulted in numerous PID controller auto-tuning patents and commercial controller units over the last several decades [7]. Among the patented and implemented PID adaptation approaches the so-called analytical formula methods, typically based on process open-loop (input step) or closed-loop (limit-cycle) excitation test are usually preferred over more complex tuning methods, such as those based on heuristic rules, artificial intelligence and numerical optimization approaches. In latter cases the closed-loop behavior is typically monitored with the PID controller turned on, and PID controller adaptation is performed in real-time without applying a dedicated test signal [8].

The conventional formula-based tuning methods, such as the Ziegler–Nichols (ZN) tuning rules, even though still used in practical applications due to their simplicity, may result in a relatively large closed-loop step response overshoot and related weak response damping [9,10]. The closed-loop damping issues have been traditionally addressed by using the Chien–Hrones–Reswick (CHR) ZN rule modification based on the time-domain FOPDT process model identification, while the so-called Kappa-Tau method has been used for frequency response-based (i.e. ultimate point finding) auto-tuning [11,12]. Some of the more recent efforts at ZN-rule improvement have included controller parameters numerical optimization for a wide range of FOPDT process model parameters variations [5], and on-line adaptation of the PID controller proportional gain [10].

In order to further improve the PID controller performance compared to the above traditional tuning formulas, a wide range of process excitation-based auto-tuning approaches has been proposed in the literature over the last decade or so, which may be categorized as

- *Frequency response-based approaches* aimed at (i) improved gain and phase margin estimation [13–15], (ii) process model identification based on closed-loop relay experiment in combination with internal model control (IMC) based controller tuning for improved control-loop load disturbance rejection [16], (iii) using a more general case of binary noise signal for the process model frequency characteristic identification and loop-shaping-based controller tuning for robust behavior [17], (iv) use of Bode's integrals for improved closed-loop system robustness [18], and (v) relay experiment with cascaded

* Corresponding author. Tel.: +385 1 6168 325; fax: +385 1 6168 351.
E-mail addresses: danijel.pavkovic@fsb.hr (D. Pavković), Sinisa.Polak@ina.hr (S. Polak), davor.zorc@fsb.hr (D. Zorc).
[1] Tel.: +385 1 6168 436; fax: +385 1 6168 351.

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PI controller for load disturbance compensation and filtering effect during process model identification [19]. For a rather comprehensive review of relay-feedback frequency-domain auto-tuning methods the reader is also referred to [20].

- *Time response approaches* based on (i) process output multiple integration and regression analysis in order to find the parameters of a second-order plus dead-time (SOPDT) process model [21], (ii) multiple process step response integration to find a general linear process model [22–24] combined with the utilization of the so-called magnitude optimum criterion in order to achieve well-damped closed-loop response, and (iii) step-response identification of FOPDT model combined with IMC tuning approach [25,26], or a robust loop-shaping controller design (the so-called AMIGO method) [26,27].
- *Combined approaches* wherein the time-domain and frequency-domain process model identification is used, such as the combined relay experiment+step response identification of a FOPDT process model [28], or a random signal-based process excitation and SOPDT process model parameters estimation and controller tuning based on zero-pole conditioning (canceling) [29].

However, in most of the above cases the PID controller tuning was based on the relatively simple FOPDT (or SOPDT) process model approximation with first-order Taylor or Padé dead-time approximations used for the purpose of PID controller design, which may not be accurate in the presence of more pronounced higher-order process dynamics. In order to capture the higher-order dynamics, while simultaneously having a relatively simple dead-time-free process model formulation, an n-th order lag process model (the so-called PTn model) can conveniently be used, wherein analytical relationships between the PTn model and FOPDT model parameters are typically given through the equivalence of the process model step response flexion tangent (the so-called Strejc method) [30,31]. By utilizing the PTn process model as the basis for the control system design in [32], straightforward analytical expressions have been derived for the PID controller parameters based on the magnitude optimum criterion (see e.g. [33] and references therein). The PTn model parameters have been identified in [32] by using the so-called moment method (see e.g. [30]), implemented through multiple time-weighted integrations of the process output, thus avoiding the estimation of the process step response flexion tangent slope (and related measurement noise issues). Since the main advantage of the magnitude optimum criterion is that it can assure a well-damped (over-damped) closed-loop system response, this approach has also been pursued for a wider class of linear process models in [22]. Further refinements of the tuning method from [22] have included a filtering term added to the PID controller transfer function to facilitate relatively straightforward closed-loop response speed (response time) tuning [23], and extending the PID controller with a reference pre-filtering or weighting action to facilitate separate closed-loop system tuning with respect to reference and external disturbance [24].

Still, the aforementioned magnitude optimum-based PID controller auto-tuning does not provide a straightforward way of closed-loop damping adjustment, while the repetitive integration of process output may result in an increased computational burden of the PID controller auto-tuning algorithm, especially if application on a relatively low-cost industrial controller is considered. Hence, a more flexible pole-placement-like tuning method, as well as a simpler process step response-based auto-tuning experiment (e.g. based on a single integration of process step response) would result in a more accommodating and less-demanding PID auto-tuner realization. To this end, this paper proposes a PID controller tuning approach based on the so-called damping optimum criterion [34,35] in combination with the PTn process model formulation, which facilitates an analytical and straightforward way of adjusting both the closed-loop response damping and response speed with respect to process dynamics. The estimation of PTn process model parameters is based herein on the single integration of the process step response in order to find the parameters of the basic FOPDT process model. The simpler FOPDT model is then related to the equivalent dead-time-free PTn model by using a higher-order Taylor expansion of the dead-time (pure delay) dynamic term via simple analytical expressions. The proposed PID controller tuning, the FOPDT and PTn process model identification procedures and the resulting PID controller auto-tuning algorithm is verified by means of extensive computer simulations.

The paper is organized as follows. Section 2 presents the analytical control system design procedure based on the damping optimum criterion and the compact PTn aperiodic process model, and illustrates the effectiveness of resulting closed-loop damping and response speed tuning method. These results are also accompanied by the analysis of the closed-loop robustness with respect to modeling uncertainties. The identification of PTn process model, based on a single integration of the process output is described in Section 3. The proposed identification procedure and the related PID controller auto-tuning are thoroughly tested in Section 4 by means of simulations. Concluding remarks are given in Section 5.

2. Control system design

This section presents the damping optimum criterion-based tuning of the PID controller for the process model with aperiodic step response dynamics, including the compact-form PTn process model. The effectiveness of the proposed PID controller tuning procedure, including the closed-loop damping tuning is illustrated by means of simulations.

2.1. Control system structure

The structure of the linear control system comprising a modified PID feedback controller (the so-called I+PD controller, [41]) is shown in Fig. 1. In comparison with the traditional PID controller where the proportional (P), integral (I), and derivative (D) terms are placed into the path of the control error e, the proportional and derivative terms of the modified PID controller act upon the measured process output y only (Fig. 1). By opting to use the modified PID controller structure which does not introduce additional controller zeros in the closed-loop transfer function, the desired closed-loop system behavior can be achieved with respect to the external disturbance w, while also avoiding the potentially excessive control effort related to sudden reference y_R changes or "noisy" reference. Since the proposed control system design does not introduce additional closed-loop zeros due to controller P+D action, the proposed approach also results in relatively simple

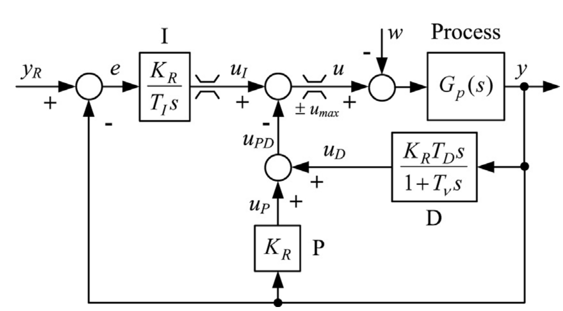

Fig. 1. Block diagram of control system with modified PID controller.