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Research Article

A fast closed-loop process dynamics characterization

Miroslav R. Mataušek*, Tomislav B. Šekara

Faculty of Electrical Engineering, University of Belgrade, Belgrade 11120, Serbia

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ABSTRACT

Stable, integrating and unstable processes, including dead-time, are analyzed in the loop with a known PI/PID controller. The ultimate gain and frequency of an unknown process $G_p(s)$, and the angle of tangent to the Nyquist curve $G_p(i\omega)$ at the ultimate frequency, are determined from the estimated Laplace transform of the set-point step response of amplitude r_0. Gain $G_p(0)$ is determined from the measurements of the control variable and known r_0. These estimates define a control relevant model $G_m(s)$, making possible the use of the previously determined and memorized look-up tables to obtain PID controller guaranteeing desired maximum sensitivity and desired sensitivity to measurement noise. Simulation and experimental results, from a laboratory thermal plant, are used to demonstrate the effectiveness and merits of the proposed method.

1. Introduction

The importance of control relevant process dynamics characterization is discussed in detail in an overview paper [1], and reexamined recently in [2]. One of the basic conclusions from [1,2] follows the idea from [3], where it is proposed to estimate a high-order ARX model first and then to perform a model reduction in the frequency domain, to obtain a reduced-order model used for controller tuning.

Three problems are related to the adequate control relevant process dynamics characterization: the model structure, the control relevant region of frequencies and the dilemma open-loop versus closed-loop process identification.

Closed-loop system performance/robustness tradeoff strongly depends on a priory knowledge defined by the structure of the model used for the PID controller tuning. The two parameter model, obtained from the Ziegler–Nichols time domain tuning [4], can be used to tune PID controller for lag-dominated processes $G_p(s)$ [5]. This model is known at the present time as integrator plus dead-time (IPDT) model. Its relationship with the Ziegler–Nichols frequency domain tuning is discussed in detail in [5]. The second one, used for the controller tuning, is the three parameter model. It is represented by the first-order plus dead-time (FOPDT) model, introduced first by Cohen–Coon [6], and by the integrating first-order plus dead-time (IFOPDT) model. FOPDT model can be used to approximate balanced and dead-time dominated processes, while IFOPDT model defines a better approximation of the lag-dominated processes, than the IPDT model [7]. The four parameter second-order plus dead-time (SOPDT) model, and other reduced-order models, used for the PI/PID controller tuning, are summarized in [8]. Mathematical models are always an approximation of reality. Appearance of a dead-time in a model might be a consequence of low-order modeling [9,10], for example based on the FOPDT, IFOPDT or SOPDT models, or might be a consequence of the real time-delay caused by some physical phenomena [11].

The control relevant region of frequencies is the region around the ultimate frequency ω_u of a process $G_p(s)$. This is confirmed by the PI/PID controller optimization [12–15], based on the frequency response of the process $G_p(i\omega)$, under constraints on the robustness. The frequency ω_0, where the sensitivity function has its maximum, occurs in the region around the ultimate frequency ω_u, as demonstrated in [14]. The importance of the process dynamics characterization based on the ultimate frequency estimation is firstly recognized by Ziegler and Nichols [4] and further developed by Åström and Hägglund [16,17]. The extension of the Ziegler–Nichols process dynamics characterization proposed in [14], by introducing an additional parameter in the frequency domain, improved considerably the possibility of better process modeling in the wider region of frequencies around the ultimate frequency ω_u of a large class of stable processes, processes with oscillatory dynamics, integrating processes and unstable processes $G_p(s)$, including dead-time.

Dilemma open-loop versus closed-loop process identification in academia is treated mainly as a problem of ensuring the best statistical accuracy [1,3]. However, in industry, breaking of control loops in operation is mainly ignored by plant operators. When some initially tuned controller is in operation, a procedure for fine tuning can be easily accepted if it can be activated/deactivated

* Corresponding author. Tel.: +381 11 337 01 64; fax: +381 11 324 86 81.
E-mail addresses: matausek@etf.rs (M.R. Mataušek), tomi@etf.rs (T.B. Šekara).

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without breaking control loops in operation [18]. A special attention should be devoted when estimating parameters of a continuous model including dead-time. For example, this can be done by applying the extended polynomial closed-loop identification [9], or to obtain model parameters, including dead-time, from the estimated frequency response of the process, obtained from the closed-loop step response tests [10,11]. However, in these methods, the dead-time free part of the model transfer function must be specified, based on some a priory knowledge, and different model structure is used for stable, integrating and unstable processes.

In this paper, a new insight into the problem of control relevant process dynamics characterization and an effective solution of this problem is presented. It is based on a continuous model $G_m(s)$ with the unified structure for a large class of stable processes, processes with oscillatory dynamics, integrating processes and unstable processes $G_p(s)$, including dead-time. Proposed in [14] as an effective extension of the Ziegler–Nichols process dynamics characterization in the frequency domain, this model is defined by the quadruplet $\{k_u, \omega_u, \varphi, A\}$. Parameter k_u is the ultimate gain and $\varphi = \arg(\partial G_p(i\omega)/\partial\omega)|_{\omega=\omega_u}$ is the angle of the tangent to the Nyquist curve $G_p(i\omega)$ at the ultimate frequency ω_u of a process $G_p(s)$. In this model an equivalent dead-time τ is defined by $\tau = \varphi/\omega_u$. Two procedures [15,18] are proposed for estimating the quadruplet $\{k_{uest}, \omega_{uest}, \varphi_{est}, A_{est}\}$. Parameter $A_{est} = A_0$ is defined in the frequency domain by $A_0 = 2|\partial G_p(i\omega)/\partial\omega|^{-1}_{\omega=\omega_u}/k_u$ [15]. The new PLL (phase-locked-loop) estimator [15], further improved in [5], requires only that the controller in operation is a linear controller, while the relay SheMa estimator [18] does not require this preliminary information. Estimation methods [5,15,18] are performed without breaking the loop containing a controller in operation. The model $G_m(s)$, defined by the quadruplet $\{k_{uest}, \omega_{uest}, \varphi_{est}, A_{est}\}$, approximates the Nyquist curve of a large class of stable processes, processes with oscillatory dynamics, integrating and unstable processes $G_p(s)$, including dead-time, in a large region around ω_u, and can be effectively used in PID controller constrained optimization [5].

However, from the industry viewpoint, disadvantage of estimation methods [5,15,18] can be a longer period of time required for determining the quadruplet $\{k_{uest}, \omega_{uest}, \varphi_{est}, A_{est}\}$. Namely, determination of φ_{est} and A_{est} by applying PLL and SheMa estimators requires two additional experiments, as explained in Appendix A. Besides, and this is of essential importance, the basic definition of parameter $A = \omega_u k_u G_p(0)/(1 + k_u G_p(0))$ [14] offers the possibility to classify a large class of stable processes, processes with oscillatory dynamics, integrating and unstable processes, including dead-time, in the $\rho - \varphi$ plane [19], where $\rho = \kappa/(1+\kappa)$, $\kappa = k_u G_p(0)$. Stable and unstable processes are classified as processes inside and outside the region $0 < \rho < 1$, $0 < \varphi < \pi/\sqrt{\rho+1}$, while the integrating processes are classified as processes with $\rho = 1$, $0 < \varphi < \pi/\sqrt{2}$, since $G_p(0) = \pm\infty$.

The possibility to classify stable processes, processes with oscillatory dynamics, integrating, and unstable processes, including dead-time, in a two parameter plane, is important from the PID controller tuning viewpoint. The desired performance/robustness tradeoff can be obtained by applying the previously memorized process independent look-up tables in this $\rho - \varphi$ plane [19]. However, to be effective, such a possibility must be supported by a fast estimation of the quadruplet $\{k_u, \omega_u, \varphi, G_p(0)\}$. Then, from the estimated $\{k_u, \omega_u, \varphi, G_p(0)\}$ and the previously memorized look-up tables one obtains directly the gains and the noise filter time constant of a real parallel PID controller, as presented in Appendix B, for stable processes and illustrated by experimental results.

In the present paper a new simple and effective closed-loop procedure is proposed for estimating quadruplet $\{k_u, \omega_u, \varphi, G_p(0)\}$ in a short time interval, without braking the loop with the controller in operation. It is assumed that the controller in operation is a known linear controller. The estimation procedure is defined in Section 2. In Section 3, a test batch, consisting of stable processes, process with oscillatory dynamics, integrating and unstable processes, including dead-time, in the loop with PI and PID controllers, is used to demonstrate the properties of the proposed estimation method. Finally, in Section 4, the experimental verification of the proposed method is presented. The quadruplet $\{k_{uest}, \omega_{uest}, \varphi_{est}, G_{pest}(0)\}$ is determined by applying a PI controller to a laboratory thermal process [20], with noisy measurements, and used for the PID controller tuning by applying the previously memorized look-up tables in the $\rho - \varphi$ plane, presented in Appendix B.

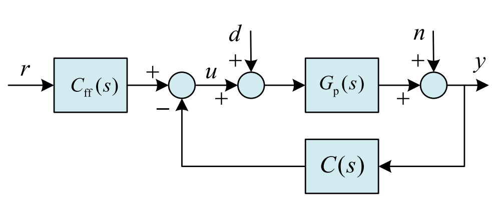

Fig. 1. Process $G_p(s)$, with a two-degree-of-freedom controller. The set-point $r(t)$, controlled variable $y(t)$, control variable $u(t)$, load and output disturbances, $d(t)$ and $n(t)$, represent variations around their values in the nominal regime.

2. Determination of the quadruplet $\{k_u, \omega_u, \varphi, G_p(0)\}$ from the closed-loop system set-point step response

Model $G_m(s)$ of an unknown stable process, process with oscillatory dynamics, integrating process and unstable process,

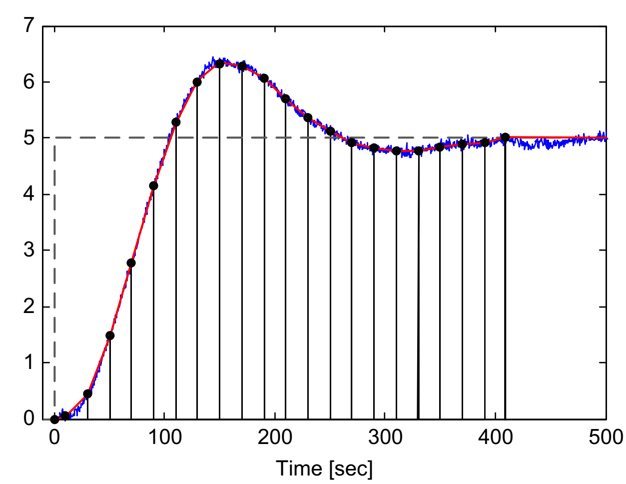

Fig. 2. The set-point (dashed), the measured closed-loop response $y(mT_s)$ of the real plant (solid-blue), the data y_j (circles-black) and $y_{id}(t)$, defined by (solid-red) lines for $0 \le t \le 400$ s, obtained by linear interpolation of y_j. For $t > 400$ s the response is approximated with its value defined by the known set-point $r_0 = 5$ and presented also by solid-red line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Parameters of the controllers used to obtain closed-loop set-point step responses for processes $G_{pl}(s)$, $l = 1,2,\ldots,7$.

Process/controller	k	k_i	k_d	T_f	b
$G_{p1}(s)$/PI	2.1631	4.7980	0	0	1
$G_{p2}(s)$/PI	0.7903	0.0654	0	0	1
$G_{p3}(s)$/PI	0.1204	0.0946	0	0	1
$G_{p4}(s)$/PID1	0.5620	0.0830	1.0620	0.1770	0
$G_{p5}(s)$/PI	0.1010	0.00255	0	0	1
$G_{p6}(s)$/PI	1.3273	0.01354	0	0	0.15
$G_{p7}(s)$/PI	0.3553	0.0030	0	0	0.25