ISA Transactions 57 (2015) 245–253

Contents lists available at ScienceDirect

ISA Transactions

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

Identification of non-minimum phase processes with time delay in the presence of measurement noise

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form
15 March 2015
Accepted 30 March 2015
Available online 15 April 2015
This paper was recommended for publication by A.B. Rad

Keywords:
Non-minimum phase
Relay with hysteresis
Limit cycle
Time domain
Measurement noise

ABSTRACT

Time domain based generalized analytical expressions are derived to estimate the exact model parameters of a class of stable non-minimum phase (NMP) processes with time delay. The novelty of the proposed method lies in generalizing a second order plus time delay (SOPDT) NMP process model in terms of a class of models like first order plus time delay (FOPDT), SOPDT underdamped, critically damped and integrating processes. The mathematical expressions are employed to estimate four accurate parameters at a time. Relay with hysteresis reduces the effect of noise and further mitigation of noise is achieved through a denoising block yielding a clean process output. Processes modeled in the form of transfer functions are considered to validate the technique.

1. Introduction

Process identification plays a significant role in the analysis of process operation and model based controller design. Relay feedback based methodologies have found wide acceptance in the estimation of unknown parameters in complex industrial processes modeled as transfer functions and their subsequent control design. Recently, Liu et al. [1] presented a detailed tutorial review on identification of process dynamics using relay or step feedback test. Several identification methods utilizing the describing function approximation (DFA) approach have been reported in the literature [2–5], wherein the equivalent gain of the relay is obtained and utilized in addition to the limit cycle parameters leading to identification of the unknown process dynamics. However, accuracy of the identified process is crucial from the perspective of an effective control design for the concerned process. Meanwhile, adopting a DFA approach is incompetent in yielding exact estimation of process model parameters. Thereafter, the design of exact identification methods using relay feedback gained high momentum. In consequence, exact techniques were developed for the estimation of unknown parameters in all pole processes with dead time as evident from the works cited in [6–13].

Numerous identification methods have been proposed in order to identify the process dynamics of all pole minimum phase processes with time delay. In contrary, few methods are reported in regard to the identification of NMP processes with time delay adopting a relay feedback approach. Panda et al. [14] presented relay based algorithms for parameter estimation of integrating processes with dead time and also addressed the response of the process with a zero in the numerator. Majhi [15] introduced a set of expressions applying ideal relay resorting to a state space based approach for estimation of process model parameters of NMP processes i.e. stable processes consisting of single or multiple poles with or without time delay. In furtherance, the work also emphasized the problem of NMP process identification in the presence of output noise. In order to circumvent the problem, a Fourier series based curve fitting technique was employed resulting in a clean limit cycle output. The method proposed by Majhi [15] could effectively estimate a maximum of three parameters among four unknowns in the transfer function model. However, the model structure considered by Majhi [15] and that in Liu and Gao [16] has repeated poles and hence cannot be generalized for the modeling of underdamped and integrating processes. The proposed work is motivated by the methods suggested in [15,16]. Padhy and Majhi [17] have deduced analytical expressions for the identification of processes exhibiting a NMP behavior with and without dead time

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http://dx.doi.org/10.1016/j.isatra.2015.03.015
0019-0578/

using ideal relay and state space based approach. Nevertheless, the authors have not considered the effects of measurement noise at the process output. Wang et al. [18] proposed an identification scheme for second and higher order process dynamics, applying fast Fourier transform (FFT) to find the frequency response of the system and thereafter an inverse fast Fourier transform (IFFT) to construct the step response of the process. Nonetheless, relay feedback testing is advantageous in the sense of being a time efficient method for identification of processes with large time constants [19]. Ramakrishnan and Chidambaram [20] suggested algorithms for the identification of SOPDT process dynamics employing an asymmetrical relay test and Laplace transform technique and the case studies were conducted considering a second order NMP process with time delay. Recently, Bajarangbali et al. [21] have proposed a time domain based algorithm for estimation of FOPDT and SOPDT process model parameters. Moreover, the authors have considered a zero in the numerator of an overdamped SOPDT process. Furthermore, the authors have addressed the crucial issue concerning the presence of measurement noise at the system output adversely effecting the correctness of system identification. In this perspective, a denoising block was proposed to achieve noise mitigation and thereafter yielding a denoised limit cycle output.

The contribution of the paper focuses on the identification of NMP process dynamics, subsuming the generalization or rather an approximation of the second order NMP process model in terms of FOPDT and SOPDT NMP process models with repeated and non-repeated poles, respectively along with online elimination of measurement noise. The ideology of the work presented in [8,21] is extended to derive analytical expressions for identification of NMP processes employing relay with hysteresis. Practically, as a matter of fact, the output of any real time process is corrupted with measurement noise, leading to chattering in the process output. This in turn lends a lower degree of accuracy in process model parameters estimation eventually invoking difficulty in an effective control design, leading to operational performance degradation. In the proposed method, a noise free limit cycle is obtained with the help of a modified denoising block. Hence, the presented technique enforces noise alleviation, yielding an excellent estimation of unknown process model parameters and is shown to work well in real time scenarios. In the literature identification methods are available for a particular type of process, few authors have considered more than one type of process but without noise. The proposed identification method can be applied to more than one type of process in the presence of measurement noise. This entire paper is systematically organized as follows. The proposed identification method is given in Section 2, analytical expressions are derived in Section 3, procedure to conduct the test is explained in Section 4, efficiency and accuracy of the proposed methodology is illustrated through simulation case studies in Section 5 and finally conclusions are drawn in Section 6.

2. Identification method

The closed loop identification scheme as shown in Fig. 1 consists of a relay with hysteresis, the NMP process and a denoising block. In Fig. 1, r is the reference or setpoint input, e is input to the relay and u and y are the process input and output, respectively. During process identification with relay input, the system generates sustained oscillations hence, the reference input (r) is made zero. Assuming that the process output is corrupted due to measurement noise, this noisy output $\bar{y}$ is passed through the modified denoising block (consisting of a derivative block and an integrator in the closed loop) to eliminate the noise effect. The derivative block (D) generates first derivative output in terms of the rate of change of noisy limit cycle $\bar{y}$ with reference to time and the integrator ($1/s$) removes higher order harmonics present in the derivative output, assuming zero initial conditions. This output is again fed back to the relay hence, the combined effect of relay with hysteresis and denoising block yields a noise free output y. The user defined relay parameters and the measured limit cycle quantities are substituted in the respective analytical expressions to estimate the unknown model parameters of NMP processes. The generalized transfer function model of a second order stable NMP process with time delay is given as

$$G_m(s) = \frac{K(-ns+1)e^{-\theta s}}{ps^2+qs+1} \tag{1}$$

which consists of the unknown parameters to be estimated as K (the steady state gain), θ (the process time delay), n (the zero on right half of the s-plane (RHP)), p and q (the process parameters). The NMP process model mentioned in (1) has a zero on RHP. These NMP characteristics can be observed in some complex chemical systems [22], Zhang et al. [23] described ship's path control system in restricted waters as a NMP system. A process with time delay or second order and higher order process with RHP zero can be considered as NMP process. The drum-boiler dynamics [24] represent one of the real time examples for NMP process. A few more real time processes are a valve control system (FOPDT or SOPDT underdamped), a telescope azimuth angle control system (SOPDT critically damped) [25] and water level in boiler drum (SOPDT integrating) [14,26].

The process model as given in (1) is considered for different types of NMP processes like FOPDT, SOPDT underdamped, critically damped and integrating. The relay input causes the process to generate limit cycles which are in the form of sustained oscillations and carry the process information. Also the delayed relay output provides two constant piecewise linear inputs to the process for the time ranges $t_\varepsilon \le t \le t_d$ and $t_d \le t \le (T+t_\varepsilon)$, where T is the half period of limit cycle, t_ε is the time at which the relay switches from $+h$ to $-h$ (h is the relay amplitude), t_d is the time at which the second derivative output of the limit cycle experiences instant change, in case of FOPDT processes, t_d is measured from the first derivative output.

3. Analytical expressions for parametric estimation

In this section a state space method is applied to derive the analytical expressions which are used to estimate the unknown process model parameters with the help of relay and limit cycle information. The state and output equations of a system consisting of a process with time delay θ are written, respectively, as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{b}u(t-\theta) \tag{2}$$

$$y(t) = \mathbf{c}\mathbf{x}(t) \tag{3}$$

where $\mathbf{x}(t)$ is the process state vector, $y(t)$ is the process output, $u(t-\theta)$ is the delayed relay output, $\mathbf{A}$ is a square matrix of the order 2 , $\mathbf{b}$ is 2×1 column vector and $\mathbf{c}$ is 1×2 row vector. As mentioned earlier the delayed relay output provides two piecewise constant inputs to the process with different time ranges hence, the solution of (2) for $t_\varepsilon \le t \le t_d$ is given as

$$\mathbf{x}(t) = \mathbf{e}^{\mathbf{A}(t-t_\varepsilon)}\mathbf{x}(t_\varepsilon) + \mathbf{A}^{-1}(\mathbf{e}^{\mathbf{A}(t-t_\varepsilon)} - \mathbf{I})\mathbf{b}h \tag{4}$$

Similarly, the solution of (2) for $t_d \le t \le (T+t_\varepsilon)$ becomes

$$\mathbf{x}(t) = \mathbf{e}^{\mathbf{A}(t-t_d)}\mathbf{x}(t_d) - \mathbf{A}^{-1}(\mathbf{e}^{\mathbf{A}(t-t_d)} - \mathbf{I})\mathbf{b}h \tag{5}$$

The limit cycle is symmetrical due to the equality of half cycles hence, the following equation holds true: