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Closed-loop step response for tuning PID-fractional-order-filter controllers

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ABSTRACT

Analytical methods are usually applied for tuning fractional controllers. The present paper proposes an empirical method for tuning a new type of fractional controller known as PID-Fractional-Order-Filter (FOF-PID). Indeed, the setpoint overshoot method, initially introduced by Shamsuzzoha and Skogestad, has been adapted for tuning FOF-PID controller. Based on simulations for a range of first order with time delay processes, correlations have been derived to obtain PID-FOF controller parameters similar to those obtained by the Internal Model Control (IMC) tuning rule. The setpoint overshoot method requires only one closed-loop step response experiment using a proportional controller (P-controller). To highlight the potential of this method, simulation results have been compared with those obtained with the IMC method as well as other pertinent techniques. Various case studies have also been considered. The comparison has revealed that the proposed tuning method performs as good as the IMC. Moreover, it might offer a number of advantages over the IMC tuning rule. For instance, the parameters of the fractional controller are directly obtained from the setpoint closed-loop response data without the need of any model of the plant to be controlled.

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1. Introduction

Recently, much interest is devoted to FOPID (Fractional-Order Proportional-Integral-Derivative) controllers. The FOPID has been introduced by Podlubny in 1999 [13] and, in the same paper, a better closed-loop response of this type of controller than the classical PID was demonstrated when used to control fractional order systems. Indeed, they provide more flexibility in the controller design. However, the tuning of this kind of controller can be much more complex because they have five parameters to be tuned [9,21]. Several research activities are devoted to develop new effective tuning techniques for non-integer order controllers by an extension of the classical control theory. In [8], the authors propose a novel adaptive genetic algorithm (AGA) for the multi-objective optimization design of a fractional PID controller and apply it to the control of an active magnetic bearing (AMB) system. In [11], an auto-tuning method of fractional order controllers is presented and the experimental platform Basic Process Rig 38-100 Feedback Unit has been used to test the fractional order controllers designed. Several other tuning techniques have been developed. Among them, the most well known are the empirical Ziegler–Nichols tuning rules. Recently, these methods (Ziegler–Nichols-type rules) are generalized for tuning fractional PID controllers, see [20] and they have been improved in the course of time and reported in several papers [1,2,19]. The Ziegler–Nichols method has some advantages and several disadvantages. Indeed, it can venture into unstable regions while testing the P-controller causing the system to be out of control, may not work well on all processes and it is known that the recommended settings are quite aggressive for lag-dominant processes [4,17]. Therefore, Shamsuzzoha and Skogestad presented an alternative empirical tuning method of an unidentified process [15] for tuning classical PID parameters. This method, based on closed loop experiment with proportional only control, is similar to the classical Ziegler–Nichols experiment, but the process is not forced to its stability limit. This method works well on a wide range of processes. It works also for delay-dominant processes because it requires much more information about the process than the Ziegler–Nichols method [16]. Note that the majority of methods proposed for tuning fractional controllers parameters are analytical methods based on a plant model. In this paper we propose to use an empirical method for tuning fractional controller parameters to control an unidentified process which is the setpoint overshoot

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method. In this paper the objective is the generalization of the idea of Shamsuzzoha and Skogestad proposed in [15] to the fractional controllers. Some changes were made to this method in order to adapt it for tuning the new kind of fractional PID controllers which is the PID-Fractional-Order-Filter Controllers (FOF-PID) proposed by Bettayeb and Mansouri in [5,6]. The PID-Fractional-Order-Filter Controller (FOF-PID) has a very interesting structure because it can be decomposed in two transfer functions; an integer PID controller and a fractional filter [6]. The main issue of the tuning method presented here is to derive correlation between the setpoint response data and the PID-FOF-controller settings calculated with the internal model control method (IMC) [14].

2. Preliminary

2.1. Bode's ideal transfer function

The ideal shape of the open-loop transfer function suggested by Bode [7] has the form,

$$L(s)=\frac{1}{\tau_c\ s^{\lambda+1}} \tag{1}$$

where $(\lambda+1)$ is the fractional order, λ is a real, and $0<\lambda<1$. The amplitude of $L(s)$ is a straight line of constant slope $-20(\lambda+1)$ dB/dec and its phase is a horizontal line at $-(\lambda+1)\pi/2$ rad. The phase does not depend on the value of the gain but only on the non-integer order. Thus it exhibits important properties such as infinite gain margin and constant phase margin. The unit feedback system with Bode's ideal transfer function inserted in the forward path is then

$$f(s)=\frac{1}{1+\tau_c s^{\lambda+1}} \tag{2}$$

This choice of $L(s)$ as an open-loop transfer function gives a closed-loop system robust to process gain variations and the step response exhibits iso-damping property (the overshoot depends only on λ). It is this feature which is often sought in the fractional controllers design. In this work, $f(s)$ is used as a reference model to tune the controller parameters. It has two adjustable parameters, the closed-loop time constant (τ_c) and the real λ which intervenes in the fractional order. When the performance of the closed-loop is specified in the frequency domain, these parameters are deduced from the gain crossover frequency ω_c and the phase margin φ_m [14,15].

$$\lambda=\frac{\pi-\varphi_m}{\pi/2}-1 \tag{3}$$

$$\tau_c=\frac{1}{\omega_c^{\lambda+1}} \tag{4}$$

because the step response of $f(s)$ (when $0<\lambda<1$) is similar to that of an underdamped second-order system for which the damping ratio is $(0<\zeta<1)$. Some other useful formulae characterizing the time response of $f(s)$ are given in [3].

1. The overshoot M_p of the step response is

$$M_p=\frac{y_{max}-y(\infty)}{y(\infty)}=0.8\lambda(\lambda+0.25) \tag{5}$$

with $0<\lambda<1$

2. The settling time T_s (for 2% and 5% criteria) is

$$T_s(2\%)\approx\frac{4}{\cos\left(\pi-\frac{\pi}{(\lambda+1)}\right)\tau_c^{\frac{-1}{\lambda+1}}} \tag{6}$$

with $0.39<\lambda<1$

$$T_s(5\%)\approx\frac{3}{\cos\left(\pi-\frac{\pi}{(\lambda+1)}\right)\tau_c^{\frac{-1}{\lambda+1}}} \tag{7}$$

with $0.44<\lambda<1$

So, when the performance of the closed-loop is specified in the time domain, the fractional order λ can be deduced from the overshoot M_p and the closed-loop constant time τ_c can be deduced from the settling time T_s.

Remark 1. The objective of our method is to obtain a system with the same performances as the performances of the fractional order model (reference model) and not necessarily all the performances (in time domain and frequency domain) of the integer order model used to calculate the fractional order model, because the integer order model is not exactly equal to the fractional model.

2.2. Internal model control

A more comprehensive model-based design method, internal model control (IMC), was developed by Morari and coworkers [12]. The IMC method, as the direct synthesis method usually used in the conventional feedback control, is based on assumed process models and leads to analytical expressions for the controller settings. The IMC approach has the advantage that it allows model uncertainty and tradeoffs between performance and robustness to be considered in a more systematic way. Furthermore, it guarantees internal stability of the closed-loop system. Indeed, the closed-loop system is stable if the IMC-controller $C_{IMC}(s)$ and the system to be controlled $G(s)$ are both stable.

The IMC paradigm is based on the simplified block diagram shown in Fig. 1.

The block diagram for the conventional feedback control is given in Fig. 2. The two block diagrams are identical if controllers $C(s)$ and $C_{IMC}(s)$ satisfy the relation

$$C(s)=\frac{C_{IMC}(s)}{1-C_{IMC}(s)G_m(s)} \tag{8}$$

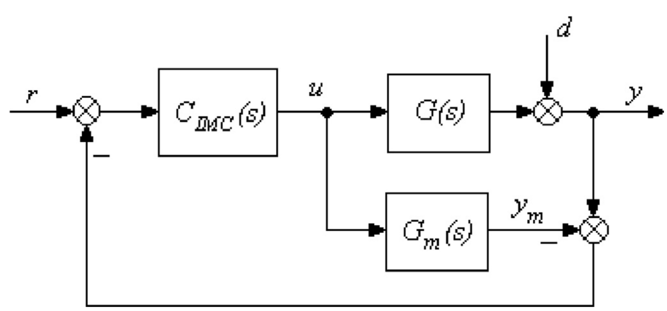

Fig. 1. Internal model control structure.

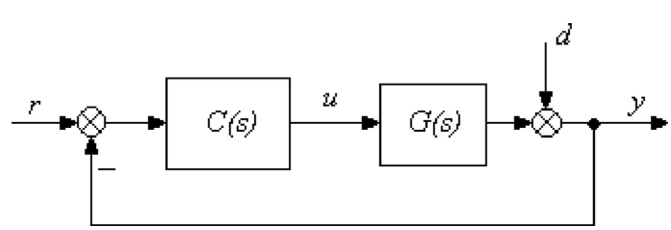

Fig. 2. Conventional feedback control.

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