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Practice Article

Incorporation of fractional-order dynamics into an existing PI/PID DC motor control loop

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ABSTRACT

The problem of changing the dynamics of an existing DC motor control system without the need of making internal changes is considered in the paper. In particular, this paper presents a method for incorporating fractional-order dynamics in an existing DC motor control system with internal PI or PID controller, through the addition of an external controller into the system and by tapping its original input and output signals. Experimental results based on the control of a real test plant from MATLAB/Simulink environment are presented, indicating the validity of the proposed approach.

1. Introduction

Fractional calculus offers novel modeling tools for the analysis of dynamical systems. In particular, memory-like, hereditary, or self-similarity phenomena arising in physical systems are better described by models based on noninteger differential [1,2]. In control engineering fractional process models have been proposed and successfully applied to describe certain systems [3,4]. The fractional-order PID controller has been proposed in [5] and further studied in [6]. Such a controller has more tuning freedom and a wider region of parameters that may stabilize the plant under control. It has been confirmed that fractional-order PID controllers offer superior performance than their integer-order counterparts; in particular, in application to servo system control [7–9]. Tuning methods for FOPID controllers were presented in, e.g., [8,10–14].

It is a known fact that the majority of industrial control loops are of PI/PID type [15]. It is therefore of significant interest to study the problem of enhancing conventional PID controllers by introducing additional dynamical properties arising from making use of fractional-order integrators and differentiators. However, introducing changes into existing control loops may require termination of an industrial process and thereby potentially result in production losses. Integrating a fractional-order controller into a working loop in a non-intrusive way is therefore beneficial, and forms the main motivation of the present paper.

In this work, the following problem is addressed. A DC motor control system is considered described by a conventional first-order plus dead time (FOPDT) plant represented by $P(s)$ and having the general form

$$P(s) = \frac{K_m}{sT_m + 1} e^{-L_m s}, \tag{1}$$

where it is assumed without loss of generality that $K_m, L_m, T_m > 0$,

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and a controller represented by $C(s)$ which could either be a classical proportional-integral (PI)

$$C_{PI}(s) = K_P + \frac{K_I}{s}, \tag{2}$$

or proportional-integral-derivative (PID) controller

$$C_{PID}(s) = K_P + \frac{K_I}{s} + K_D s, \tag{3}$$

where $K_P, K_I, K_D > 0$ are also assumed within a unity-feedback system. By combining the plant (1) and one of the controllers in (2) or (3), it can be seen that step and frequency responses will follow integer-order dynamics since the resulting denominator polynomial of the total transfer functions is governed by an integer-order polynomial.

The objective of the control algorithm proposed in this paper is to change the dynamics of the entire DC motor control system by incorporating fractional-order dynamics and eliminating the original influence of the classical PI or PID controllers, without making internal changes into the system. In particular, the objective is to make the entire system follow certain fractional-order dynamics. The latter can be achieved by using a fractional-order PID (FOPID) controller designed subject to particular specifications.

The contribution of this paper is as follows. First, the proposed retuning algorithm is described. Next, the design of a suitable FOPI or FOPID controller for an industrial process is detailed. The complete algorithm is then applied to a real-life model of an industrial object—a modular servo system—thereby indicating the validity of the proposed method through real-time experiments.

The novelty of the paper lies in experimental verification of the retuning method thereby expanding the results achieved only through simulations in [16]. Similar practical results are not known from prior art. Our earlier contribution [17] focuses on a different application of the retuning algorithm for a different type of plant. In this work, the choice of the experimental setup is based on the finding [7] that fractional-order controllers provide superior control characteristics compared to conventional ones in case of servo control.

The structure of the paper is as follows. In Section 2 the reader is introduced to basic concepts of fractional-order modeling. The proposed control architecture and tuning algorithm are detailed in Section 3. The description of the real-life servo system is given in Section 4, where, in addition, the dynamic model of the velocity control process is identified, and conventional PI and PID controllers are designed following a set of classical tuning rules. The application of the retuning method is illustrated in Section 5. Finally, conclusions are drawn in Section 6.

2. Brief introduction to fractional-order modeling and control

Fractional calculus is a generalization of integration and differentiation to the non-integer order operator ${}_a\mathcal{D}_t^\alpha$, where a and t denote the limits of the operation [8]. The continuous integro-differential operator of order $\alpha \in \mathbb{R}$ is defined in the following way

$${}_a\mathcal{D}_t^\alpha = \begin{cases} \mathrm{d}^\alpha/\mathrm{d}t^\alpha & \alpha > 0, \\ 1 & \alpha = 0, \\ \int_a^t (\mathrm{d}\tau)^{-\alpha} & \alpha < 0. \end{cases} \tag{4}$$

In this paper we consider Caputo's definition of the fractional operator which is given by

$${}_0^C\mathcal{D}_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)} \int_0^t \frac{f^{(m)}(\tau)}{(t-\tau)^{\alpha-m+1}}\,\mathrm{d}\tau, \tag{5}$$

where $m-1 < \alpha < m, m \in \mathbb{N}$, $\alpha \in \mathbb{R}_+$. The reason for adopting this definition is the practical applicability thereof, since it offers physically coherent meaning of initial conditions when solving corresponding fractional differential equations [1].

Assuming zero initial conditions, the Laplace transform of the fractional derivative in (5) is given by

$$\int_0^\infty \mathrm{e}^{-st}\,{}_0\mathcal{D}_t^\alpha f(t)\,\mathrm{d}t = s^\alpha F(s). \tag{6}$$

Thus, a fractional-order transfer function with a delay may be considered in the s-domain such that

$$G(s) = \frac{b_m s^{\beta_m} + b_{m-1} s^{\beta_{m-1}} + \cdots + b_0 s^{\beta_0}}{a_n s^{\alpha_n} + a_{n-1} s^{\alpha_{n-1}} + \cdots + a_0 s^{\alpha_0}} \mathrm{e}^{-Ls}, \tag{7}$$

where it is usual to take $\beta_0 = \alpha_0 = 0$, in which case the static gain of the system is given by $K = b_0/a_0$.

In real-life applications approximations of fractional-order operators are often used. In this work, Oustaloup's approximation method is considered. It is described in [18]. The method allows one to obtain a band-limited approximation of a fractional-order differentiator or integrator in the form $s^\alpha \approx H(s)$, where $\alpha \in (-1, 1)$ and $H(s)$ is a conventional continuous-time linear system. The following approximation parameters are considered: filter order N such that the resulting integer-order model order is $2N+1$, and frequency band limits (ω_b, ω_h). The continuous-time representation can be used for digital filter implementation by applying a proper discretization method [19].

3. New control architecture and tuning algorithm

Consider an ordinary unity-feedback control system consisting of a controller $C(s)$ and plant $P(s)$. The controller $C(s)$ is assumed to be either of PI or PID type tuned to stabilize the plant. The feedback control system therefore follows the rules of integer-order differential equations. The objective is to plug in an external fractional-order controller $C_R(s)$ into the existing control system in such a way that the dynamics of the overall system follows the rules governed by fractional-order differential equations. The control architecture with an external controller incorporated into an existing feedback control system is shown in Fig. 1. The results of this paper are partially based on results in [20], where a retuning method for a conventional integer-order PI/PID was studied. The extension of these results for FO controllers brings about a considerable amount of benefit due to additional tuning flexibility and the ability to satisfy more design specifications such as the often desired iso-damping property of the control loop. The external fractional-order controller $C_R(s)$ captures the input and output signals of the original feedback control system and feeds a corrective signal in addition to the input signal into the feedback control system [16,21]. The effect of a double feedback configuration in Fig. 1 is equivalent to a simple unity-gain feedback control system with the controller

$$C^*(s) = (C_R(s) + 1)C(s) \tag{8}$$

as shown in Fig. 2.

3.1. Retuning control architecture

Let us consider the FOPDT plant in (1). In what follows, several propositions related to the suggested control system retuning architecture are provided.

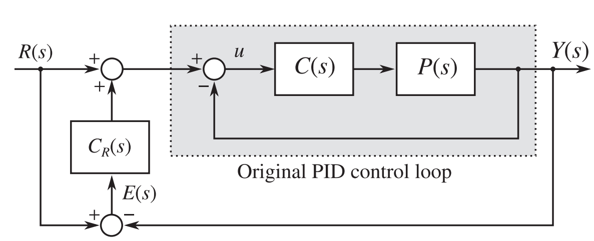

Fig. 1. The retuning architecture where an external controller $C_R(s)$ is added into the system without compromising the internal connection of the original closed-loop system.