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Generalized multi-scale control scheme for cascade processes with time-delays

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ABSTRACT

The cascade control is a well-known technique in process industry to improve regulatory control performance. The use of the conventional PI/PID controllers has often been found to be ineffective for cascade processes with long time-delays. Recent literature report has shown that the multi-scale control (MSC) scheme is capable of providing improved performance over the conventional PID controllers for processes characterized by long time-delays as well as slow RHP zeros. This paper presents an extension of this basic MSC scheme to cascade processes with long time-delays. This new cascade MSC scheme is applicable to self-regulating, integrating and unstable processes. Extensive numerical studies demonstrate the effectiveness of the cascade MSC scheme compared with some well-established cascade control strategies.

1. Introduction

One of the most common control strategies adopted in process industry in order to improve disturbance rejection performance is the cascade control strategy introduced in [1]. Many process control textbooks advocate the benefits of cascade control strategy, i.e., see [2–4]. One of the well-known benefits of cascade control strategy is the ability to correct for certain disturbances in advance before they can seriously influence the primary or main controlled variable.

One well-known example of cascade control application is in reactor temperature control, e.g., polymerization reactor [5]. Here, the cascade control strategy uses the jacket reactor temperature as an extra measurement (secondary output). The role of the secondary controller is to quickly reject any disturbance that initially affects the jacket reactor temperature before the disturbance can seriously affect the primary reactor temperature.

A number of researchers have extensively studied the applications of cascade control scheme to single-input and single-output (SISO) stable processes, e.g., see works by [6–10]. However, much fewer number of researchers have focused on the design of cascade control strategies for unstable or integrating processes with long time-delays. The design of cascade control for these types of processes has been known to be a challenging task due to the presence of unstable modes and delays, which often impose limitation on the achievable control performance. For stable (non-cascade)SISO processes with time-delays, one can improve the regulatory control performance by using the classical Smith predictor [11]. Interestingly, some researchers have also proposed extensions of the classical Smith predictor to SISO non-self-regulating (integrating/unstable) processes, e.g., see works on modified Smith predictors in [12–14]. Additionally, several cascade control strategies based on the Smith predictor have also been developed for non-self-regulating processes with time-delays. Among these cascade control strategies based on the Smith predictor are the schemes reported in [15–21]. It should be noted that, the existing modified Smith predictor schemes for the unstable and integrating cascade processes require the design of several controllers. Hence, these Smith predictor-based cascade control systems are rather difficult to design and implement in practice.

In this work, we present a new cascade control strategy constructed based on the SISO multi-scale control (MSC) scheme recently reported in Nandong and Zang [22,23]. The key principle of the MSC scheme is to decompose a given plant into a sum of basic modes with distinct speed of responses. It follows that an individual sub-controller is specifically designed to control each of the plant modes. Finally, an overall multi-scale controller is synthesized by combining all of the sub-controllers in such a way that the faster sub-controller is used as a slave to a slower sub-controller; in other words, the sub-controllers are assembled in a cascaded manner. The rationale behind this cascaded combination of all the

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sub-controllers is to enhance the cooperation among the different plant modes in order to optimize the overall control performance. The works by Nandong and Zang [22,23] have demonstrated that this MSC scheme is able to provide improved nominal performance as well as performance robustness over some well-established control schemes for the nonminimum-phase (NMP) processes. The main novelty of the present work is to extend this SISO MSC scheme to cascade processes which are characterized by long time-delays, where the processes could be stable or integrating or unstable.

The rest of this paper is laid out as follows. In Section 2, some relevant preliminaries are presented. We also describe the basic idea of the multi-scale control (MSC) scheme for a single-input and single–output (SISO) process. Then in Section 3, we present the extension of this basic MSC scheme to cascade processes as well as a general controller design procedure. Section 4 provides some illustrative examples to demonstrate the effectiveness of the proposed cascade MSC scheme as compared to some well-established cascade control schemes. Section 5 finally highlights some concluding remarks and future works.

2. Preliminaries

2.1. Standard cascade control strategy

Fig. 1 depicts the block diagram of a standard (conventional) cascade control scheme, which consists of a secondary process P_2 cascaded with a primary process P_1. Note that, for the cascade control scheme to work effectively, the secondary control-loop must be faster than the primary control-loop. With respect to Fig. 1, the secondary controller G_{c2} is often referred to as a slave controller while the primary controller G_{c1} as a master controller. Here, D_1 and D_2 represent the input and output disturbance (w.r.t. secondary process) signals, respectively.

Based on Fig. 1, the closed-loop transfer function from the master controller output E to the secondary process output Y_2 is given as

$$H_{RS} = \frac{Y_2}{E} = \frac{G_{c2}P_2}{1 + G_{c2}P_2} \tag{1}$$

Meanwhile, the closed-loop transfer function from the external setpoint R to the primary process output Y can be expressed as follows

$$H_{RP} = \frac{Y}{R} = \frac{F_r G_{c1} H_{RS} P_1}{1 + G_{c1} H_{RS} P_1} \tag{2}$$

where F_r denotes the setpoint pre-filter. The setpoint pre-filter is normally a first order transfer function with a unity gain. The filter time constant can be tuned to give a desired setpoint tracking response, e.g., to achieve a desired overshoot for setpoint tracking.

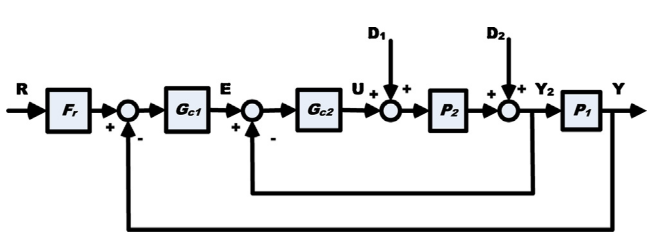

Fig. 1. Conventional two-level cascade control strategy.

2.2. Plant decomposition

Consider a rational transfer function P (with numerator N and denominator D), which can be decomposed via partial fraction expansion into a sum of $n+1$ factors or modes as follows:

$$P = \frac{N}{D} = P_0 + P_1 + P_2 + \ldots + P_n \tag{3}$$

where P_i, $\forall i \in \{0, 1, 2, \ldots, n\}$ is the plant factor or mode, which is either a first- or second-order system with real coefficients. The plant factors in (3) are arranged from the slowest factor P_0 to the fastest P_n, i.e. the dynamic of P_i is slower than that of P_{i+1} for $i = 0, 1, 2, \ldots, n-1$. Here, P_0 is called the outermost factor and P_i, $\forall i \in \{1, 2, 3, \ldots, n\}$ the inner-layer factor.

2.3. Deadtime approximation

When a given plant model contains a deadtime or time-delay component, the time-delay component is first approximated by a rational transfer function before the plant decomposition is performed as in (3). One of the approximation approaches for the deadtime component is based on the Padé rational approximation [24]:

$$e^{-\theta s} \approx G_{td} = \frac{L_n(-s)}{L_n(s)} \tag{4}$$

where

$$L_n(s) = \sum_{j=0}^{n} \binom{n}{j} \frac{\theta^j (2n-j)!}{(2n)!} s^j = \sum_{j=0}^{n} \frac{\theta^j (2n-j)! n!}{(2n)!(n-j)! j!} s^j \tag{5}$$

The first-order or 1/1 Padé formulae is often sufficient for many practical applications

$$e^{-\theta s} \approx G_{td} = \frac{1 - (\theta/2)s}{1 + (\theta/2)s} \tag{6}$$

After approximating the time-delay using either (4) or (6), one can then decompose the approximated plant model as follows

$$P_m = P_{mo} e^{-\theta s} \approx P_{mo} G_{td} = P_0 + P_1 + \ldots + P_n \tag{7}$$

where P_{mo} denotes the delay-free part of the plant model P_m and θ the time-delay.

2.4. Fundamental of multi-scale control scheme

Fig. 2 shows the realization block diagram of a 2-layer multi-scale control (MSC) scheme for a single-input and single-output (SISO) process; see [22,23] for further details. The block diagram shown in Fig. 2 implies that the given plant P can be decomposed into a sum of 2 factors or modes with distinct speeds of responses (time-scales) to a similar input. Here, K_0 and K_1 denote the sub-controllers corresponding to the outermost and inner-layer factors, respectively; W_1 is called the multi-scale predictor.

For the 2-layer MSC scheme (Fig. 2), the multi-scale predictor is chosen as

$$W_1 = \bar{P}_1 \tag{8}$$

where $\bar{P}_1$ denotes the nominal model for the plant factor P_1. The inner-loop of the MSC scheme (Fig. 2a) can be reduced to a standard single-loop feedback control (Fig. 2b). Based on Fig. 2b, we can write the closed-loop inner-layer transfer function as follows

$$G_1 = \frac{K_1}{1 + K_1 W_1} \tag{9}$$

The augmented overall plant transfer function is given by

$$P_c = G_1 P \tag{10}$$