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Simultaneous closed-loop tuning of cascade controllers based directly on set-point step-response data

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ABSTRACT

This study presents a novel closed-loop tuning method for cascade control systems, in which both primary and secondary controllers are tuned simultaneously by directly using set-point step-response data without resorting to process models. The tuning method can be applied on-line to improve the performance of existing underperforming cascade controllers by retuning controller parameters, using routine operating data. The goal of the proposed design is to obtain the parameters of two proportional-integral-derivative (PID)-type controllers, so that the resulting inner and outer loops behave as similarly as possible to the appropriately specified reference models. The tuning rule and optimization problem related to the proposed design are derived. Based on the rationale behind cascade control, the secondary controller is designed based on disturbance rejection to quickly attenuate disturbances. The primary controller is designed to accurately account for the inner-loop dynamics, without requiring an additional test. In addition, robustness considerations are included in the proposed tuning method, which enable the designer to explicitly address the trade-off between performance and robustness for inner and outer loops independently. Simulation examples show that the proposed method exhibits superior control performance compared with the previous (model-based) tuning methods, confirming the effectiveness of this novel tuning method for cascade control systems.

1. Introduction

Cascade control is one of the most successful schemes for enhancing the performance of single-loop control, particularly when disturbances are associated with the manipulated variable [1]. Therefore, cascade control has been applied extensively in chemical process industries. In the standard cascade-control approach, one feedback loop is nested inside another feedback loop using two controllers. The controller of the inner loop is called the secondary (or slave) controller, and the controller of the outer loop is the primary (or master) controller. The rationale behind this configuration is that the fast dynamics of the inner loop enable fast attenuation of disturbances, and minimize the possible effects of disturbances before they affect the primary output, which is the controlled variable of interest.

Although sophisticated schemes for cascade control have been proposed [2–4], the basic scheme still comprises two nested loops with two proportional-integral-derivative (PID) controllers. Because this scheme involves tuning two controllers, the design of cascade control systems is more complex than the design of single-loop control systems. The usual approach involves first tuning the secondary controller by setting the outer loop open. The primary controller is then tuned while considering the action of the secondary controller on the inner loop. This two-step tuning procedure is time-consuming, because two runs of the plant test (step or relay test) are typically required [5,6]. The sequential tuning procedure has been improved so that only a single experiment is conducted for tuning the two controllers simultaneously [7–12]. However, usually an off-line or ad hoc experiment must be performed in these methods. For example, Leva and Donida [7] performed a test with a relay cascaded to an integrator, and Mehta and Majhi [8] restricted the secondary controller to a P controller during the relay test. Veronesi and Visioli [12] proposed a simultaneous closed-loop automatic tuning method for cascade controllers based on a set-point step test. However, their method required knowledge of the existing controllers.

In most methods for simultaneous tuning, low-order models (usually first-order plus time delay models) of the primary and secondary processes are first identified, and then the two PID controllers are tuned using model-based tuning rules [8,11,12]. Using these methods, it is relatively simple to tune the secondary controller, whereas tuning the primary controller is more complex

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because an additional low-order apparent model (usually second-order plus time delay model), which represents the lumped dynamics of the primary process and the inner loop, is required. Two difficulties may be encountered in identifying such an apparent model. First, because the primary process usually exhibits high-order dynamics, low-order modeling of the primary process introduces inevitable modeling errors. Second, the inner-loop dynamics is approximated using the inner-loop design target (e.g., a desired closed-loop transfer function of the inner loop) [8,12–14] and then augmented with the primary process model to obtain a low-order apparent model. However, this approximation may be inaccurate because the implemented secondary controller cannot guarantee meeting the inner-loop design target. Consequently, the large modeling error associated with the apparent model diminishes both the effectiveness of model-based design for tuning the primary controller and the performance of cascade control. Jeng and Lee [15] proposed a simultaneous tuning method for cascade control in which the identified apparent model could accurately account for the actual inner-loop dynamics using a frequency-domain identification technique. However, the apparent model still contains modeling errors that result from model reduction.

An attractive approach for alleviating the drawbacks of plant-model mismatch is to design PID controllers directly from a set of process input and output data, without resorting to process models. Because the measured plant data contain more direct and useful information on plant dynamics than mathematical models developed through system identification, direct approaches for controller design are expected to provide effective controllers that reflect the dynamics of a plant. Several mode-free or data-based methods for designing controllers have been developed [16–21]. Given a set of process input–output data, these methods can be used to determine the controller parameters, so that the corresponding closed-loop response is as close to a predefined (desired) reference trajectory as possible. Controller designs have typically been developed based on servo-response consideration, which may result in sluggish disturbance response for processes exhibiting lag-dominant dynamics. Previous studies have addressed the data-based design of controllers for unitary feedback systems, but using data-based methods to design controllers for cascade control systems has not been reported. In addition, amendment to the existing data-based design methods based on disturbance rejection is worthwhile because cascade control is mainly devoted to improving the suppression of inner-loop disturbance.

Using data-based methods for designing controllers for cascade control systems is even more attractive than applying these methods to single-loop control systems, because identifying process models for cascade control systems is more complex and time-consuming than it is for single-loop systems. Therefore, we aimed to extend the data-based method of controller design to cascade control systems for simultaneous tuning of two controllers by directly using closed-loop plant data. The proposed method can be used on-line to design two PID controllers in a cascade structure without depending on the availability of process models. In addition, knowledge of the existing controller parameters is not required. The design of cascade controllers achieves satisfactory servo and regulatory control performances, using the standard cascade control configuration (i.e., complicated control schemes are not used); this is accomplished by designing the inner loop for enhanced attenuation of disturbance and by considering the actual inner-loop dynamics in the primary controller design (without an additional experiment). Furthermore, robustness considerations of the inner and outer loops are explicitly included in the proposed procedure for controller tuning.

The rest of this paper is organized as follows. Section 2 presents the structure of cascade control and the collection of plant data. Sections 3 and 4 present the proposed data-based tuning method for the secondary and primary controllers, respectively. Section 5 summarizes the controller tuning procedure. Section 6 provides several simulation examples demonstrating the effectiveness of the proposed method. Finally, Section 7 offers concluding remarks.

2. Cascade control systems

In a cascade control scheme, the introduction of an additional sensor creates a secondary (inner) loop that effectively attenuates disturbances. Fig. 1 shows the configuration of a typical cascade control system, where G_1 is the primary process and G_2 is the secondary process. The primary controller G_{c1} uses the primary process variable y_1 (with set-point r_1) to establish the set-point (r_2) for the secondary controller G_{c2}. The secondary process variable y_2 is transmitted to the secondary controller, which adjusts the manipulated variable u. Disturbances can enter at two possible points, d_1 and d_2, with disturbance transfer functions G_{d1} and G_{d2}, respectively. A cascade control scheme is effective because the disturbance d_2 affecting the inner loop is promptly compensated before it affects the primary process variable y_1. Because derivative action is rarely used in the secondary loop [1], this study considered that the secondary controller is a PI controller and the primary controller is a PID controller.

It is assumed that the processes $G_1(s)$ and $G_2(s)$ are unknown and only a set of process input-output data, $u(t)$, $y_2(t)$, and $y_1(t)$, are available for tuning two controllers. The required plant data can be obtained by conducting a one-shot closed-loop plant test. Compared with the open-loop test, the closed-loop test is desirable because the process can be conducted continuously throughout the entire test. In this respect, the proposed tuning method plays a vital role in improving existing controllers that underperform (i.e., poorly tuned controllers). Moreover, only the closed-loop test can be used for non-self-regulating processes. The set-point step test was considered in this study because it is the simplest and most widely used test in process control applications. Thus, the proposed tuning procedure can exploit routine operating data. The process variables, $y_1(t)$ and $y_2(t)$, and the manipulated variable, $u(t)$, during the set-point step change are collected until a new steady-state is

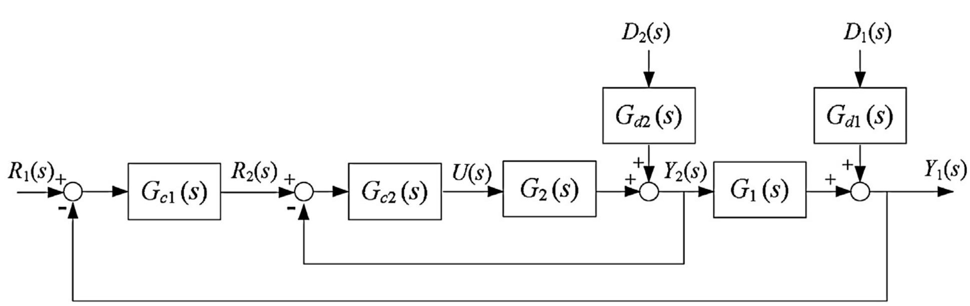

Fig. 1. Configuration of a typical cascade control system.