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Independent design of multi-loop PI/PID controllers for interacting multivariable processes

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ABSTRACT

The interactions between input/output variables are a common phenomenon and the main obstacle encountered in the design of multi-loop controllers for interacting multivariable processes. In this study, a novel method for the independent design of multi-loop PI/PID controllers is proposed. The idea of an effective open-loop transfer function (EOTF) is first introduced to decompose a multi-loop control system into a set of equivalent independent single loops. Using a model reduction technique, the EOTF is further approximated to the reduced-order form. Based on the corresponding EOTF model, the individual controller of each single loop is then independently designed by applying the internal model control (IMC)-based PID tuning approach for single-input/single-output (SISO) systems, while the main effects of the dynamic interactions are properly taken into account. Several illustrative examples are employed to demonstrate the effectiveness of the proposed method.

1. Introduction

Most chemical processes are basically multi-input/multi-output (MIMO) systems. Despite the development of advanced multivariable controllers, the multi-loop PI/PID control using multiple single-input/single-output (SISO) PI/PID controllers remains the standard for controlling MIMO systems with modest interaction because of its simple and failure tolerant structure and adequate performance [1,2]. However, due to process and loop interactions, the design and tuning of multi-loop controllers is much more difficult compared with that of single-loop controllers. Since the controllers interact with each other, the tuning of one loop cannot be done independently. Applying the tuning methods for a SISO system to multi-loop systems often leads to poor performance and stability. Much research has been focused on how to efficiently take loop interactions into account in the multi-loop controller design. Many methods have been proposed, including the detuning method, sequential loop closing (SLC) method, relay auto-tuning method, and independent loop method.

The biggest log modulus tuning (BLT) method proposed by Luyben [3] is a typical example of the detuning method, wherein each individual controller is first designed based on the Ziegler–Nichols (Z–N) tuning rules [4] by ignoring process interactions from other loops. Then, the interactions are taken into account by detuning each controller until the multivariable Nyquist stability is satisfied. The attractiveness of this method is due to the simplicity in implementation and comprehensibleness for control engineers. However, a disadvantage is that the controller settings are made more conservative.

The well-known SLC method for the design of multi-loop controllers was first introduced by Mayne [5] and later studied by Hovd and Skogestad [6]. In this method, the controllers are tuned sequentially, wherein the controller of the fastest loops should be tuned first by considering a selected input–output pair; this loop is then closed and then the controller of the lower loops is tuned for a second pair while the first control loop remains closed and so on. The SLC method is simpler than the detuning method as each controller is designed using SISO design methods.

In relay auto-tuning for the multi-loop control system [7–10], the relay feedback technique is applied to the design of each corresponding SISO controller. The control loops are tuned sequentially or simultaneously. Furthermore, on the basis of sequential algorithm, the multi-loop control system is designed in a sequence of SISO design problems and the interaction taken into account in a sequential fashion. In this way, Loh et al. [8] and Shen and Yu [9] have directly combined the efficiency of a single-loop relay and SLC method to design multi-loop controllers, which is sometimes called as the auto-tuning SLC method. These methods require minimal process information but tuning sequence has to be repeated for the correct sequence if the design sequence is not appropriate.

The independent loop method is used to surmount the restriction of the relay auto-tuning. As discussed by a number of authors

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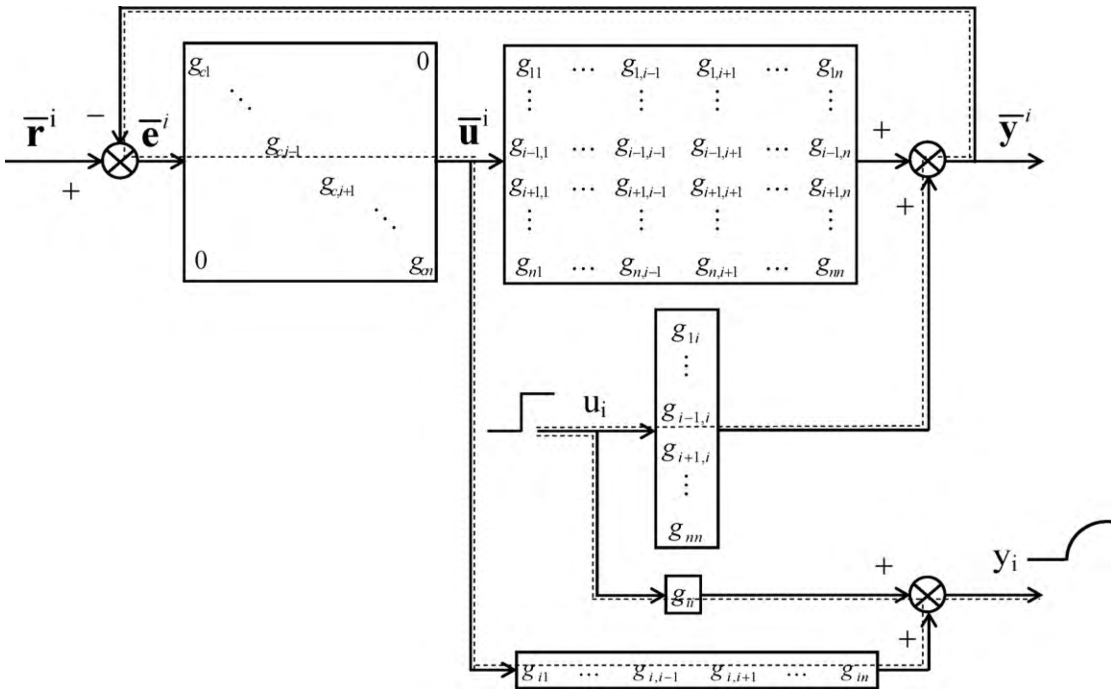

Fig. 1. Block diagram for the concept of the effective open-loop transfer function in a $n \times n$ multi-loop system: loop i is open while all other loops are closed.

[11–14], the independent loop method has a potential advantage in that the failure tolerance of the overall control system is automatically guaranteed, wherein each controller is independently designed based on the corresponding open-loop and closed-loop transfer functions, thereby satisfying the inequality constraints on the process interactions [11]. A potential disadvantage of the method is one of the conservatism due to the inherent assumption of the independent design, which does not exploit the information regarding controllers in other loops [12]. For this, the independent loop method for IMC type multi-loop controllers [13,14] is used to reduce the conservatism.

Recently, several researchers have introduced the concept of an effective open-loop transfer function (EOTF) to take into account the loop interactions in the novel design of a multi-loop controller [15–19]. Using this concept, the design of a multi-loop controller can be reasonably converted to the design of a single-loop controller. On the basis of structure decomposition, the multi-loop control system is completely separated into equivalent individual SISO loops, and thus the effects of the process and controller on the loop interaction and subsequent system properties, such as right half plane (RHP) zeros and poles, integrity, and stability, are elucidated [15]. Moreover, He et al. [16] have suggested the dynamic relative interaction to derive the multiplicative model factor (MMF) for an individual control loop; the equivalent transfer function is then obtained by multiplying the original loop transfer function with the approximated MMF within the neighborhood of the individual control loop critical frequency. Huang et al. [17] found that the EOTF is formulated without prior knowledge of controller dynamics in other loops and that the controller is independently designed for equivalent single loops. In an alternate manner, Xiong and Cai [18] suggested that the EOTF provides both gain and phase information for multi-loop controller design in four ways. The advantages of the EOTF involve reduced modeling requirements and ease of implementation while the potential disadvantage is reduction in achievable control performance due to restricted controller structure [19].

The control performance of the multi-loop systems is also closely related to the control loop pairing. Given its clear and useful definition, the well-known RGA [20] has been widely used for the multi-loop structure design, such as a ratio of an open-loop

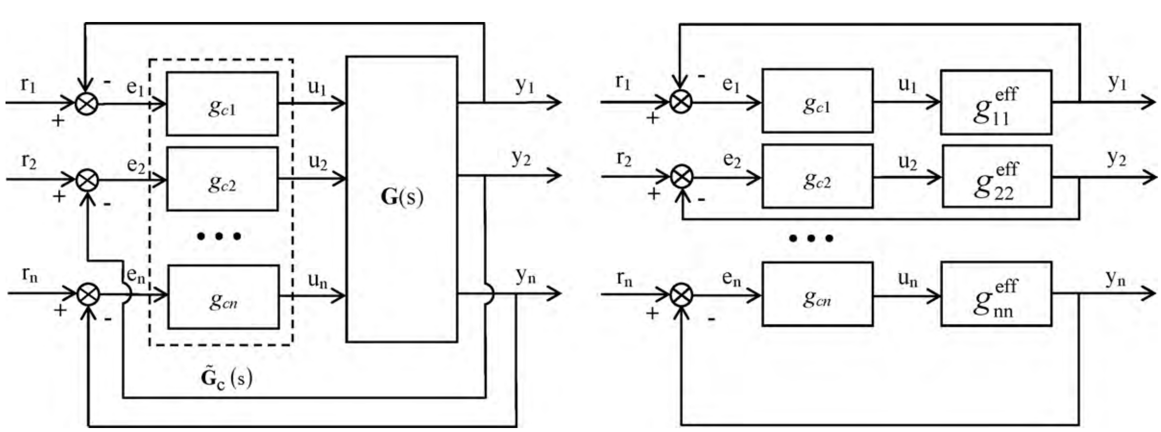

Fig. 2. Multi-loop system and equivalent independent SISO systems with the corresponding EOTFs.