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Inverted decoupling internal model control for square stable multivariable time delay systems

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ABSTRACT

This paper presents a new tuning methodology of the main controller of an internal model control structure for $n \times n$ stable multivariable processes with multiple time delays based on the centralized inverted decoupling structure. Independently of the system size, very simple general expressions for the controller elements are obtained. The realizability conditions are provided and the specification of the closed-loop requirements is explained. A diagonal filter is added to the proposed control structure in order to improve the disturbance rejection without modifying the nominal set-point response. The effectiveness of the method is illustrated through different simulation examples in comparison with other works.

1. Introduction

Time delays arise in many industrial processes as a consequence of different phenomena such as transport times of mass, information or energy; accumulation of time lags in processes interconnected in series; or processing time [1]. Time delays affect the performance of traditional control systems because they can lead to very poor system response as they prevent high controller gain from be used in order to avoid instability. The Smith Predictor (SP) was the first compensator specially designed for single-input single output (SISO) systems with time delay [2]. It allows the elimination of the time delay in the characteristic equation. In the last years, different modifications of the SP have been developed to overcome some drawbacks of its initial proposal and to improve its performance [3,4].

In multiple-inputs multiple-outputs (MIMO) systems there may be important couplings between inputs and outputs signals which may complicate the feedback controller design. In presence of time delays this design becomes even more difficult because each output is affected by each input with different time delays [5]. As a result, a transfer function matrix representation of the MIMO process is preferred in these cases [6]. Different approaches have been developed in order to design controller for multivariable systems with multiple time delays: some authors have extended the SP to the multivariable case [7–9]. In line with the previous ones, other works propose to solve the problem by means of an internal model control (IMC) applied to MIMO processes [10,11]. There is a close relationship between PS and IMC [12] since the SP can expressed in an equivalent IMC structure as shown in Fig. 1 where G_m is the multi-delay model of the plant. Others authors develop directly multivariable methodologies based on the conventional unity feedback structure: decoupling control [13–16], multivariable PID controllers [17,18], H_∞ controllers [19], or decentralized controllers [20,21]. Some of these methodologies combine PS or IMC with some of the last methods [6,22]. Others use two degree of freedom control structures in order to achieve a good performance for reference tracking and disturbance rejection separately [23,24].

In order to apply IMC to multivariable systems, two approaches can be usually found. The first one consists in designing a decoupler $D(s)$ to the original process in order to obtain a diagonal or diagonal dominant apparent process, and then, applying the IMC to this apparent process $G(s)\cdot D(s)$ (Fig. 2) [25,26]. The IMC design can be performed as that of SISO case. The second one and more common applies simultaneously decoupling control and IMC [6,27] using the scheme of Fig. 1.

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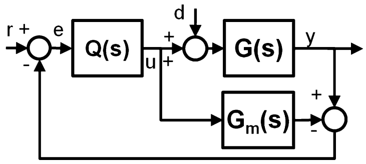

Fig. 1. IMC scheme.

From the IMC scheme in Fig. 1, the matrix expressions of the closed-loop transfer matrix $T(s)$ from the references r to the outputs y, and the transfer matrix $H(s)$ from the load disturbances d to the outputs y can be obtained as follows:

$$T(s) = G(s) \cdot Q(s) \cdot [I + (G(s) - G_m(s)) \cdot Q(s)]^{-1} \quad (1)$$

$$H(s) = G(s) - G(s) \cdot [I + Q(s)(G(s) - G_m(s))]^{-1} \cdot Q(s) \cdot G(s) \quad (2)$$

where $G(s)$, $G_m(s)$ and $Q(s)$ are the transfer matrix of the plant, the nominal model of the plant and the main controller of the IMC structure, respectively. When the model of the process is perfect, that is, $G_m(s) = G(s)$, the previous closed-loop transfer matrixes are simplified to (3) and (4).

$$T(s) = G(s) \cdot Q(s) \quad (3)$$

$$H(s) = G(s) - G(s) \cdot Q(s) \cdot G(s) = (I - T(s)) \cdot G(s) \quad (4)$$

Therefore, the main controller $Q(s)$ can be calculated from (3) after defining the closed-loop transfer matrix $T(s)$ properly for realizability and stability. Most of multivariable IMC methodologies use a transfer matrix $Q(s)$ in which the process inputs u are derived by a time-weighted combination of the error signals e. If decoupling is required in $T(s)$, the main problem of such methods is the increase of the design complication when the size of the system is large, because the calculations become more complex and important approximations are usually required. For instance, an analytical decoupling IMC method is developed in [11] on the basis of the H_2 optimal performance objective. It uses the IMC scheme of Fig. 1 and complex controller elements are obtained for the ideal optimal control matrix even for 2×2 processes.

This work proposes a new tuning methodology of the main controller of an IMC structure for directly decoupling and stabilizing square stable multivariable processes with multiple time delays. It is based on the structure of centralized inverted decoupling [28] that allows obtaining very simple expressions for controller elements independently of the system size. However, as disadvantage, it cannot be applied to processes with multivariable zeros in the right half plane (RHP) since it results unstable. The paper is structured as follows. In Section 2, the proposed method is developed for $n \times n$ processes. Several aspects as realizability are discussed. The equivalency between multivariable IMC and centralized inverted decoupling control schemes is shown. In order to improve disturbance rejection a diagonal filter in the feedback loop is proposed. Section 3 illustrates the methodology with several simulation examples. Finally, conclusions are summarized in Section 4.

2. Inverted decoupling IMC

2.1. General expressions for $n \times n$ processes

Assuming a stable square process $G(s)$ with n inputs and n outputs, the proposed methodology uses the centralized inverted decoupling control to design the control matrix $Q(s)$ obtaining a decoupled response in $T(s)$. As shown in Fig. 3, $Q(s)$ is split into two blocks: a matrix $Qd(s)$ in the direct path (between the error signals e and the control signals u) and a matrix $Qo(s)$ in a feedback loop (in the opposite direction). According to the inverted decoupling structure, $Qd(s)$ must have only n elements different from zero which connect the error signals e with the control signals u. In order to decouple the system, $Qo(s)$ feeds back the control signals u toward the controller inputs. $Qo(s)$ must have only n zero elements, which correspond with the transpose non-zero elements of $Qd(s)$. For example, in a 4×4 process, if element $Qd(1,4)$ is selected as a direct connection between u_1 and e_4, there will not be feedback from u_1 to e_4 and consequently, $Qo(4,1)$ must be zero.

From the representation in Fig. 3 and from the general IMC Eq. (3), the expression of the elements of $Qd(s)$ and $Qo(s)$ can be calculated by means of (5).

$$Qd^{-1}(s) - Qo(s) = T^{-1}(s) \cdot G(s) \quad (5)$$

This main expression is quite similar to that obtained for the centralized inverted decoupling control in [28]. However, in this method, the desired open-loop transfer matrix $L(s)$ used in [28] is replaced by the desired closed-loop transfer matrix $T(s)$ because of the IMC structure. Afterward, the design equations are practically the same of [28]. Nevertheless, the tuning procedure using $T(s)$ instead of $L(s)$ allows specifying the desired nominal performance in a more direct and easier way than that used in [28]. In the last one, using the classical control feedback scheme, specifications need to be translated to the open-loop transfer functions from the closed-loop requirements.

Assuming that the desired closed-loop response is a decoupled response from the references to the outputs, the matrix $T(s)$ must be diagonal. Then, the main advantage of (5) over expressions of conventional multivariable IMC methods is its simplicity, regardless of the size of the process, because the resulting subtraction of $Qd^{-1}(s)$ and $Qo(s)$ is a transfer matrix with only one element to be calculated for each position.

Note that $Qd(s)$ has to be non-singular since it is inverted, and therefore, when its non-zero elements are chosen, only one element in each row and column can be selected. As a result, for an $n \times n$ system there are $n!$ possible configurations of $Qd(s)$. To name them, the authors propose the same notation in [29], in which the indicated number corresponds to the column with the chosen element. For instance, in a 2×2 system there are two configurations: 1–2 when elements $Qd(1,1)$ and $Qd(2,2)$ are selected to be non-zero; 2–1 when elements $Qd(1,2)$ and $Qd(2,1)$ are chosen. The expression of the controller elements for each configuration is different, which is interesting because some choices can result in non-realizable elements. Therefore, the configuration can be selected depending on the realizability, which will be discussed later.

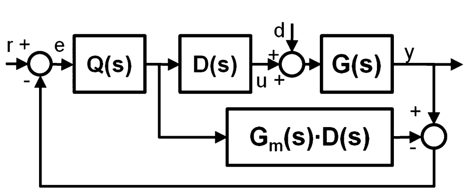

Fig. 2. IMC with decoupler scheme.

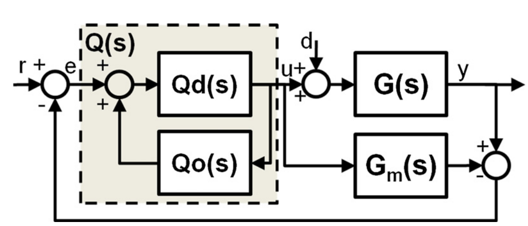

Fig. 3. Inverted decoupling IMC scheme.