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Time delay compensation for the secondary processes in a multivariable carbon isotope separation unit

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HIGHLIGHTS

- ► A novel control strategy for multivariable time delay processes is proposed.
- ► Control strategy suitable for a general class of chemical processes.
- ► Proposed control strategy is compared with the "in house" EPSAC controller.
- ► Robustness test for significant time delay uncertainties.

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ABSTRACT

Time delays occur frequently in process control systems and uncertainties regarding modeling of such phenomena limit the degree of freedom of the designed controllers. The problem is even more acute when dealing with multivariable systems. To overcome the difficulties in the controller design, Smith predictor control schemes are frequently used. The paper proposes a simple, yet efficient, novel control strategy for solving the delay time compensation problem for the secondary processes in a pilot plant cryogenic carbon isotope separation column. The authors show that compared to an exiting control strategy, the proposed method can be generally applied to any type of system. To illustrate the robustness of the proposed closed loop control scheme a more advanced control strategy is designed consisting in an EPSAC model based predictive controller. Comparative simulations, considering $\pm 50\%$ uncertainty in the multivariable time delays, show that the novel control strategy proposed in this paper offers good results both in terms of reference tracking and robustness, similar to those of the predictive controller. Additionally, the proposed control strategy has a wide area of applicability, to a general class of chemical units.

1. Introduction

Time delays are frequently encountered in process control loops (Normey-Rico and Camacho, 2008), especially in chemical processing units such as distillation plants, oil fractionators, reactors or isotope separation plants (Stephanopoulos, 1984; Wang et al., 2000). Variable time delays in feedback control loops are challenging for the purpose of optimum process operation, since they limit the degree of freedom for the control action. Additionally, most industrial plants have a nonlinear and multivariable nature. Hence, control algorithms designed for such plants must cope with a manifold of dynamic challenges and constraints.

A commonly applied solution for the time delay compensation problem for SISO processes has been firstly mentioned by Smith (1957). The proposed control structure has the great advantage of removing the delay from the closed-loop characteristic equation, with significant improvement of the setpoint tracking response performance. An extension of the SISO Smith predictor to multivariable systems has been proposed firstly for MIMO systems with single delay (Alevisakis and Seborg, 1973) and then for multiple delays (Ogunnaike and Ray, 1979). Improvements have been made to the overall performance of the MIMO Smith predictor (Jerome and Ray, 1986). A key element in all these MIMO Smith predictors is the decoupling of the process. Different strategies have been used for the design of the decoupling matrix. A modified form of the MIMO Smith predictor for processes with multiple time delays has been used by Wang et al., (2000), in which the design of the decoupling matrix is based on a frequency domain approach. Later, the internal model control (IMC) method

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has been used for the same decoupling matrix (Wang et al., 2002). Seshagiri and Chidambaram (2006) extend the MIMO Smith predictor structures to nonsquare processes represented by first order transfer functions and time delays. The decoupling is done only in steady state by using the pseudo-inverse of the steady-state gain matrix; the final controller, consisting of a matrix of PI's, is then computed using the Davison method (Davison, 1976). Robustness issues are usually tackled by filter design methods. Chen et al. (2011) start from the previously designed MIMO Smith predictor for the same type of nonsquare processes, but claim that an IMC approach smoothes the design burden for the final PI matrix of controllers and also leads to better robustness.

In this paper, we propose an improved variant of the method of Chen et al. (2011). The original method is altered by using the designed decoupling matrix as a pre-compensator. The designed IMC controller can then be directly used as a final controller, rather than as a means to compute the final PI controller matrix. The proposed method offers in this way a simplified and straightforward approach to the design of the controller. Also, the method is extended for a more general class of processes, rather than the simple first order transfer function tackled by both (Chen et al., 2011; Seshagiri and Chidambaram, 2006). For comparison, we introduce an alternative approach to time delay compensation using a model based predictive control (MPC) algorithm (Allgöwer and Zheng, 2000; Camacho and Bordons, 2004). The MPC controller implemented on the plant is the EPSAC—Extended Prediction Self-Adaptive Controller (De Keyser and Van Cauwenberghe, 1981; De Keyser, 2003). The choice for the predictive controller relies upon its inherent time delay compensation properties, as well as to the adaptive characteristics that usually trigger an increased closed loop robustness to time delay uncertainties.

The paper is organized as follows: In Section 2, the method proposed in this paper is described, as compared to the original one (Chen et al., 2011). Section 3 presents the process under study in this paper, a carbon isotope separation pilot plant. Section 4 presents the design using the IMC-Smith predictor structure for the carbon isotope separation process, while Section 5 presents the EPSAC–MPC approach. Section 6 presents comparative results using the IMC controller and the EPSAC controller. The final part contains the conclusions and some discussions.

2. Proposed dead time compensator: A MIMO approach

2.1. Original dead time compensation method for MIMO first order time delay systems: PI controller matrix

Since in this paper the multivariable time delay process is a square one, the original mathematical formulae (Chen et al., 2011) are modified for controlling these types of processes (Stephanopoulos, 1984; Wang et al., 2008). Nevertheless, the approach for non-square systems will be tackled in a subsequent section of the paper.

For a general square process with 'm' inputs and 'm' outputs, the transfer function matrix is given as (Chen et al., 2011; Seshagiri and Chidambaram, 2006):

$$G_p(s)=\begin{bmatrix} g_{11}e^{-\tau_{11}s} & \dots & g_{1m}e^{-\tau_{1m}s} \\ : & : & : \\ g_{m1}e^{-\tau_{m1}s} & \dots & g_{mm}e^{-\tau_{mm}s} \end{bmatrix} \tag{1}$$

where g_{ij} represents the first order transfer functions from the jth input to the ith output (Chen et al., 2011). The model of the process is assumed to be equal to the process transfer function matrix:

$$G_m(s)=\begin{bmatrix} g_{11}e^{-\tau_{11}s} & \dots & g_{1m}e^{-\tau_{1m}s} \\ : & : & : \\ g_{m1}e^{-\tau_{m1}s} & \dots & g_{mm}e^{-\tau_{mm}s} \end{bmatrix} \tag{2}$$

The delay free model of the process is given by

$$\tilde{G}_m(s)=\begin{bmatrix} g_{11} & \dots & g_{1m} \\ : & : & : \\ g_{m1} & \dots & g_{mm} \end{bmatrix} \tag{3}$$

The first step in the design of the primary controller is the steady state decoupling (Chen et al., 2011), achieved by computing the steady state gain matrix

$$G_m(s=0)=\begin{bmatrix} g_{110} & \dots & g_{1m0} \\ : & : & : \\ g_{m10} & \dots & g_{mm0} \end{bmatrix} \tag{4}$$

and its inverse, $G_m^{\#}$.

Consequently, the decoupling of the process can be achieved from

$$G_D(s)=G_m(s)\,G_m^{\#}=\begin{bmatrix} g_{d11} & \dots & g_{d1m} \\ : & : & \dots \\ g_{dm1} & \dots & g_{dmm} \end{bmatrix} \tag{5}$$

in which all elements are weighted sums of the original transfer functions$g_{ij}e^{-\tau_{ij}s}$. Due to the static decoupling, in steady state the transfer function matrix $G_D(s=0)$ will be equal to the unit matrix. Thus, the non-diagonal terms in the $G_D(s)$ decoupled process transfer function matrix would be zero in steady state conditions; consequently, only the diagonal terms in (5) will be further used in the design of the controller, with each diagonal term corresponding to a specific process output. The next step is to approximate the diagonal elements in the decoupled transfer function with simple first order transfer functions (Chen et al., 2011):

$$g_{dii}(s)\approx g_{dii}^{*}(s)=\frac{k_{m_i}}{T_{m_i}s+1}e^{-\tau_{m_i}s} \tag{6}$$

The approximation can be done using the graphical methods or the genetic algorithms as in Chen et al. (2011). The next step towards the design of the controller is based on IMC tuning rules, yielding a final controller in the form

$$IMC_i=\frac{T_{m_i}s+1}{k_{m_i}(\lambda_i s+1)} \tag{7}$$

with λ_i the IMC filter time constant.

In the original method of Chen et al. (2011), the next step is to compute PI controllers based on the equivalence between the traditional Smith predictor (Normey-Rico and Camacho, 2008) and the IMC control structures:

$$\mathrm{PI}_i(s)=(1-\mathrm{IMC}_i(s)\tilde{g}_{dii}^{*}(s))^{-1}\mathrm{IMC}_i=\frac{1}{\lambda_i}\frac{T_{m_i}s+1}{k_{m_i}s} \tag{8}$$

where $\tilde{g}_{dii}^{*}(s)$ is the $g_{dii}^{*}(s)$term in (6) without the corresponding time delay.

The final controller of Fig. 1(a) (Chen et al., 2011) is computed based on the decoupling matrix $G_m^{\#}$ and the $G_{PI}(s)$ controller matrix obtained using (8):

$$G_c(s)=G_m^{\#}G_{PI}(s)=G_m^{\#}\begin{pmatrix} PI_1(s) & 0 & \dots & 0 \\ 0 & PI_2(s) & \dots & 0 \\ \dots & \dots & \dots & 0 \\ 0 & 0 & \dots & PI_m(s) \end{pmatrix} \tag{9}$$