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An automatic tuning methodology for a unified dead-time compensator

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ABSTRACT

In this paper, an automatic tuning methodology for a modified Smith predictor control scheme is proposed. The main feature of the procedure is that it is applied in closed-loop (by either evaluating a set-point or a load disturbance step response) and it is suitable for self-regulating, integral and unstable processes. Further, the process parameter estimation technique is based on the evaluation of the integral of signals, thus making it inherently robust to measurement noise. Simulation and experimental results demonstrate the effectiveness of the methodology.

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1. Introduction

Dead time compensator control schemes have been widely investigated in the last 50 years because of the need of obtaining a higher and higher performance even with processes with a large dead time, which are well known to be difficult to control by means of standard feedback control systems. In fact, processes with a significant dead time are frequently encountered in industry. The time delay can be due to the transportation of material, energy, information, or can be introduced by the sensor, or can appear as a result of the series of a large number of low-order systems (Normey-Rico & Camacho, 2007; Palmor, 1996).

Many modifications have been proposed starting from the Smith predictor scheme (Smith, 1957), by trying to overcome its drawbacks (in particular, its poor robustness and its incapability to deal with processes that are not self-regulating). See for example the works (Åström, Hang, & Lim, 1994; Mataušek & Micić, 1996, 1999; Normey-Rico & Camacho, 2002; Zhong & Normey-Rico, 2002) based on simple modifications of the SP for stable and integrative models or the ones in Kwak, Whan, and Lee (2001), Kaya (2003), Chien, Peng, and Liu (2002), Hang, Wang, and Yang (2003), Tan, Marquez, and Chen (2005), Liu, Cai, Gu, and Zhang (2005), Liu, Zhang, and Gu (2005), Lu, Yang, Wang, and Zheng (2005), and Rao and Chidambaram (2005) for the unstable case. A review of these techniques can be found in Normey-Rico and Camacho (2007). A relevant methodology in this context has been proposed in Normey-Rico and Camacho (2009), which consists in using a modified structure of the Smith predictor that allows the decoupling of the disturbance rejection and set-point following tasks. In this way, the controller can be tuned in order to achieve a compromise between performance and robustness. It has to be stressed that the same approach can be used for self-regulating, integral and unstable processes. All these features, together with its overall simplicity, make this methodology very suitable to be applied in industrial settings.

However, it has also to be recognized that, for its widespread use in industry, an industrial controller should be equipped with the automatic tuning functionality, which allows the user to put the controller in place without the need of (possibly time consuming) trial-and-error procedures. Actually, the presence of well-established automatic tuning techniques is one of the reasons of the great success of Proportional-Integral-Derivative (PID) controllers (Åström & Hägglund, 2006; Visioli, 2006). For this reason, different methods have been proposed for the automatic tuning of Smith predictor based control schemes (Kaya, 2003, 2004; Majhi & Atherton, 2000; Matausek & Kvascev, 2003; Tan, Chua, Zhao, Yang, & Tham, 2009). However, all of them have been applied to control schemes which address particular issues of the dead time compensators. Further, they all need a special experiment in order to determine the process parameters upon which the controller is tuned.

In this paper we propose an automatic tuning procedure which can be applied to the unified design of the dead-time compensator

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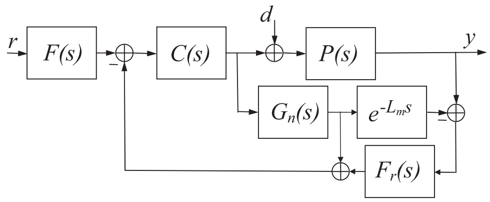

Fig. 1. The considered filtered Smith predictor scheme.

presented in Normey-Rico and Camacho (2009). The devised methodology suitably extends the process estimation parameters technique that has already been applied to the automatic tuning of PID controllers (Veronesi & Visioli, 2009, 2010a,b) and of cascade control systems (Veronesi & Visioli, 2011). In particular, the process parameters are obtained by evaluating routine operating data with the dead-time compensator control structure (possibly roughly tuned) already in place. In this context, both set-point and (measurable) load disturbance step responses can be evaluated. Integral of signals are employed so that the technique is inherently robust to measurement noise. Then, if the performance is not satisfactory (in this context, performance assessment indexes have been suitably devised), the dead-time compensator can be suitably retuned by considering the trade-off between performance and robustness.

The paper is organized as follows. In Section 2 the unified approach for the robust dead time compensator design is reviewed by highlighting the three different cases related to self-regulating, integral, and unstable processes. Then, in Section 3 the parameters estimation procedure is described for the considered kinds of processes and for both the set-point and load disturbance step responses. Performance assessment indexes and tuning rules are proposed in Section 4. Simulation results are then shown in Section 5 and experimental results are presented in Section 6. Conclusions are drawn in Section 7.

2. The modified Smith predictor

2.1. Control scheme

The control scheme considered in this paper is the filtered Smith predictor (FSP) originally proposed in Normey-Rico, Bordons, and Camacho (1997) and shown in Fig. 1, where $P(s)$ is the true process transfer function, $P_n(s)=G_n(s)e^{-L_m s}$ is the process model (i.e., $G_n(s)$ is the delay-free model and L_m is the estimated value of the dead time) and $C(s)$ is the feedback controller. Note that, with respect to the classical Smith predictor, two additional filters are employed. In particular, the set-point filter $F(s)$ is used to improve the set-point response and the predictor filter $F_r(s)$ is used to improve the predictor properties in such a way that eliminates all the drawbacks of the original Smith predictor when controlling lag-dominant or unstable plants.[1]

In fact, in case of a perfect process model, that is, $P_n(s)=P(s)$, the nominal closed-loop transfer functions are

$$H_r(s)=\frac{Y(s)}{R(s)}=\frac{F(s)C(s)P(s)}{1+C(s)G_n(s)} \tag{1}$$

and

$$H_d(s)=\frac{Y(s)}{Q(s)}=P(s)\left[1-\frac{F_r(s)C(s)P(s)}{1+C(s)G_n(s)}\right]. \tag{2}$$

[1] For stable plants, SP cannot achieve a faster disturbance rejection response than the open-loop one. For unstable plants, $F_r(s)$ allows to obtain an internally stable system, which cannot be obtained with the standard SP.

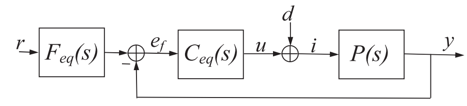

Fig. 2. The equivalent filtered Smith predictor scheme.

From (Eqs. (1) and 2) and a proper tuning, $C(s)$ and $F(s)$ can be used to define the set-point response while $F_r(s)$ can define the characteristics of the disturbance response in such a way that $H_r(s)$ and $H_d(s)$ can have different closed-loop poles, therefore decoupling the set-point and disturbance rejection responses. (Details on the design of the control scheme are presented in Normey-Rico & Camacho, 2009.) Hereafter, we briefly review the most relevant cases which will be exploited in the automatic tuning procedure that is the subject of this paper, that is, processes that can be modelled by stable, integrative or unstable first order plus dead-time systems. It is in any case worth noting that the control structure shown in Fig. 1 is used for analysis while, in order to cope with an internal instability when integral or unstable processes are to be controlled, alternative implementation should be applied (Palmor, 1996; Watanabe & Ito, 1981). In particular, as dead-time compensator structures are only implemented in digital devices, a simple implementation of the FSP in the discrete time domain can be exploited considering the scheme in Fig. 2, where the discrete-time representation of $C_{eq}(s)$ is a simple rational function in z (Normey-Rico & Camacho, 2009).

2.2. Self-regulating processes

Self-regulating (asymptotically stable) processes can be modelled, as it is industrial practice, as a first-order-plus-dead-time (FOPDT) transfer function, that is

$$P_n(s)=\frac{K_m}{T_m s+1}e^{-L_m s}. \tag{3}$$

In this case, a convenient strategy is to select $C(s)$ as a PI controller

$$C(s)=K_p\frac{T_i s+1}{T_i s} \tag{4}$$

with $T_i=T_m$ and $K_p=T/(K_m T_r)$ where T_r defines the nominal closed-loop pole of $H_r(s)=e^{-L_m s}/(1+sT_r)$ (in this case $F(s)=1$). To decouple the set-point and disturbance responses,

$$F_r(s)=\frac{(T_r s+1)(\beta_1 s+1)}{(T_0 s+1)^2} \tag{5}$$

is used, where $\beta_1=T_m[1-(1-T_0/T_m)^2 e^{-L_m/T_m}]$, giving $H_d(s)=P_n(s)[1-((1+s\beta_1)/(1+sT_0)^2)e^{-L_m s}]$ that has not a pole at $s=-1/T_m$ (Normey-Rico & Camacho, 2009). It has to be noted that T_r determines the performance with respect to the set-point step response while T_0 handles the trade-off between performance (in the load disturbance rejection task) and robustness of the control system (this point is analyzed with more details in Section 4.2).

2.3. Integral processes

In case of an integral process, the typical model applied for tuning purposes is the integrator plus dead time (IPDT) transfer function $P_n(s)=(K_m/s)e^{-L_m s}$. Using $C(s)=K_p=1/(K_m T_r)$, $F(s)=1$ and $F_r(s)$ as in (5) with $\beta_1=2T_0+L_m$ the same closed-loop characteristics ($H_r(s)$ and $H_d(s)$) as in the stable case are obtained. T_r and T_0 have the same physical meaning of the self-regulating processes case.

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