



A dead-time compensating PID controller structure and robust tuning

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ABSTRACT

In the present paper a dead-time compensating proportional-integral-derivative (DTC–PID) controller with anti-windup action is derived. The proposed controller also can be configured as a PID controller or as a dead-time compensating PI (DTC–PI) controller. For stable, integrating and unstable processes, approximated with the first-order plus dead-time (FOPDT) model, robust tuning procedure is derived for the DTC–PI controller. Optimization of the regulatory performance of the DTC–PID controller is based on the frequency response of higher-order models, under constraints on the robustness and sensitivity to measurement noise. Excellent performance/robustness trade-off is obtained for stable, integrating and unstable processes, including dead-time, as confirmed by simulations and by experimental results obtained on a laboratory thermal process.

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1. Introduction

Surveys on the current status in process control [1,2] confirms that the PID control still predominates and that “it is quite reasonable to predict that PID control will continue to be used in the future” [3]. Another group of widely applied controllers are dead-time compensators (DTCs), designed as the Smith predictor [4–6] and its modifications [7–10], or obtained by inserting a time delay into the integral feedback circuit of a PI_{τ}/PID_{τ} controller [11,12] and predictive PI controller [13,14]. Recently [15], based on a simple disturbance observer, a generalization of the series PID controller is proposed, which can be configured as PI_{τ}/PID_{τ} controller.

In the present paper, the dead-time compensating PID (DTC–PID) controller [16] is proposed, which can be configured as a PID controller or as the dead-time compensating PI (DTC–PI) controller, including anti-windup action and adequate tuning. Besides the controller structure, the a priori knowledge about the process dynamics and the desired performance/robustness trade-off are responsible for the selection of tuning procedures. They are based on some tuning rules, which are transformations of a small amount of measured process characteristics into the controller parameters, or on the controller optimization under constraints on the robustness and sensitivity to measurement noise. Both of the approaches

are applied for adjusting parameters of the proposed DTC–PID controller.

The structure of the DTC–PID is derived in Section 2. In Section 3, based on the a priori knowledge defined by the first-order plus dead-time (FOPDT) model, robust tuning rules are derived for the DTC–PI controller. Constrained DTC–PID controller optimization is performed by using the frequency response of higher-order models. In Section 4, a test batch consisting of stable, integrating and unstable processes is used for comparison with PID and DTC controllers. Experimental results are presented in Section 5.

2. Controller structure

The proposed controller is derived starting from the structure presented in Fig. 1, where:

- (1) Disturbance observer DO generates an estimate $\hat{d}(t)$ of disturbance $d(t)$ from process output $y(t)$ and actuator output $w(t)$. This estimate is used to obtain offset-free control, substituting in this way the controller integral action.
- (2) Controller SC is used to stabilize unstable/integrating processes and/or to adjust transients in the case of stable processes.
- (3) Reference prefilter G_{ff} is used to shape reference response of the closed-loop system.

Output of the controller and reference signal are denoted by $u(t)$ and $r(t)$, respectively. It is assumed that there is a local controller

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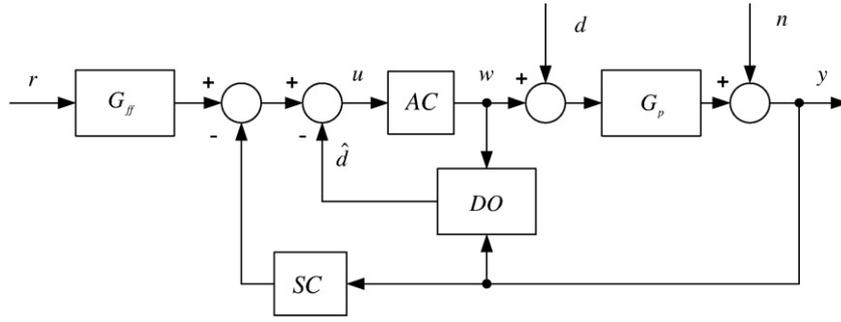


Fig. 1. General structure used to design the proposed controller: reference prefilter G_{ff} , actuator AC, process G_p , disturbance observer DO and stabilizing controller SC.

in the actuator, providing $w(t) \equiv u(t)$ in the linear region. In the present paper, actuator AC is modeled as given by

$$w(t) = \begin{cases} u(t), & l_{low} < u(t) < l_{high} \\ l_{low}, & u(t) \leq l_{low} \\ l_{high}, & u(t) \geq l_{high} \end{cases} \quad (1)$$

To derive the proposed controller structure, suppose that the process G_p dynamics is described with the following transfer function

$$G_m(s) = \frac{e^{-Ls}}{B_2(s)}, \quad B_2(s) = b_2s^2 + b_1s + b_0. \quad (2)$$

Assuming that model (2) is ideal representation of the process, from $G_p(s) \equiv G_m(s)$ and Fig. 1, one obtains the estimate $\hat{D}(s)$ in the following form

$$\hat{D}(s) = F_D(s)(B_2(s)Y(s) - e^{-Ls}W(s)), \quad (3)$$

where $\hat{D}(s)$ in (3), for $n(t) \equiv 0$, is filtered and delayed disturbance $D(s)$, given by

$$\hat{D}(s) = F_D(s)e^{-Ls}D(s). \quad (4)$$

The simplest form of the disturbance observer filter $F_D(s)$, that gives $F_D(s)B_2(s)$ proper, is defined by

$$F_D(s) = \frac{1}{(T_I s + 1)(T_F s + 1)}, \quad (5)$$

with two adjustable time constants T_I and T_F . Then, from (3) and Fig. 1, for $w(t) \equiv u(t)$, one obtains

$$Y(s) = H_{ff}(s)R(s) + H_D(s)D(s), \quad (6)$$

where the set-point and load disturbance responses $H_{ff}(s)R(s)$ and $H_D(s)D(s)$ are defined by

$$H_{ff}(s) = \frac{G_p(s)G_{ff}(s)}{1 + G_{SC}(s)G_p(s)}, \quad H_D(s) = \frac{G_p(s)(1 - F_D(s)e^{-Ls})}{1 + G_{SC}(s)G_p(s)}, \quad (7)$$

and both depend on the stabilizing controller SC, with transfer function $G_{SC}(s)$. Stabilizing controller SC is chosen to have a proportional-derivative action as defined by:

$$G_{SC}(s) = \frac{K_C + K_D s}{T_F s + 1}. \quad (8)$$

The same time constant T_F is used in (5) and (8).

Now, for the second-order polynomial $A_2(s)$ defined by

$$A_2(s) = a_2s^2 + a_1s + a_0 = B_2(s) + (K_C + K_D s)(T_I s + 1), \quad (9)$$

from (3)–(5), (8) and (9) and Fig. 1 one obtains the DTC–PID controller in Fig. 2a, defined by:

$$U(s) = (a_0R(s) - A_2(s)Y(s) + e^{-Ls}W(s))F_D(s). \quad (10)$$

When a priori knowledge about the process dynamics is used for the controller tuning, then for the given values of b_0 , b_1 and L ,

for $b_2=0$, $K_D=0$ and $T_F=0$ parameters a_0 , a_1 and a_2 are determined from (9) by adjusting K_C and T_I as in Section 3.1. When the controller tuning is based on an estimate of the frequency response of the process $G_p(i\omega)$ then the adjustable parameters defined by $q = [a_0, a_1, a_2, T_I, L]^T$, $T_F = T_I$, are determined by optimization under constraints on the robustness and sensitivity to measurement noise, as in Section 3.2. Both tuning procedures, discussed in Section 3, are used in the simulation analysis in Section 4.

The simplest reference prefilter $G_{ff}(s)$ is given by:

$$G_{ff}(s) = a_0F_D(s). \quad (11)$$

However, for better reference tracking, different reference prefilters can be chosen by adding additional dynamics and tuning parameters, keeping the value of the static gain $G_{ff}(0) = a_0$. The proposed prefilter (11) is quite satisfactory for most purposes.

2.1. Relationship between the DTC–PID and PID controller structures

It is interesting to compare the DTC–PID controller in Fig. 2a with anti-windup version of the parallel PID controller [17] in Fig. 2b,

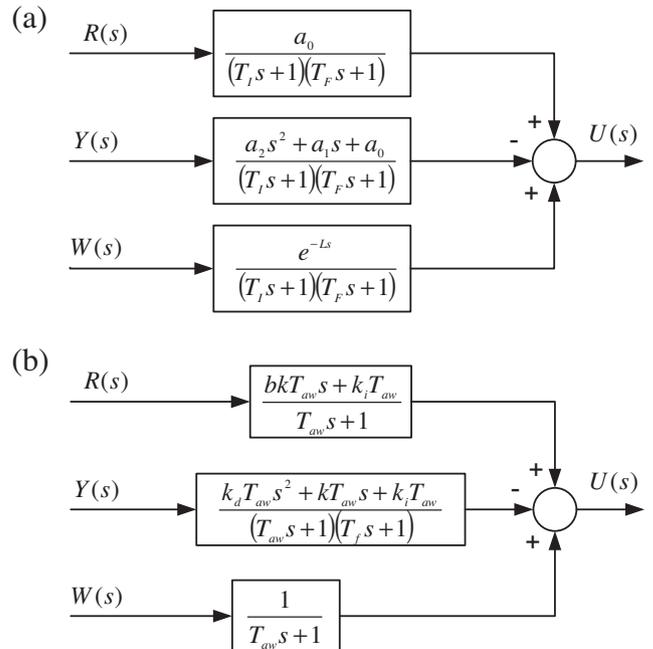


Fig. 2. Comparison between: (a) DTC–PID controller and (b) PID controller, both with anti-windup action.

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