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Comparing Equivalent Dead-Time Compensators

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Abstract: The paper deals with evaluation of some new aspects in dead-time compensators design for the first order time delayed plant. It considers several alternative solutions to the Smith predictor employing higher order low pass filters. Nominally they should yield the same dynamics. Evaluation by real time control of an Arduino based thermal plant aims to show if they are equivalent also in non-ideal practical applications. Another tested question is, if the introduction of higher order filters brings some advantages. Due to introduction of a disturbance reference model, the new modifications of the Smith predictor keep its original dynamics also under an explicit stabilizing controller. They may be derived both for input and output measurable disturbances. However, since a disturbance observer for reconstruction of non measurable output disturbances by a parallel plant model is applicable just to stable plants, from the beginning the comparison shows non identical properties of the treated solutions. The carried out experiments show also their differences in noise attenuation.

Keywords: Performance analysis, dead time compensator, Arduino-based laboratory plant.

1. INTRODUCTION

Design of two degree of freedom (2DOF) dead time compensators (DTCs) with application to the first order time delayed (FOTD) plants has been treated in several papers (Normey-Rico and Camacho, 2009; Normey-Rico et al., 2009). Hence, one could get an impression that all we need to know when dealing with such a design is already known. Recently, several new alternatives to such a design appeared. The primary motivation was given by the fact that the 2DOF Smith predictor is directly applicable just to stable plants. Formally, its 2DOF structure with a feedback filter C_o (Fig.1) may also be used for unstable plants. But, for implementation, it has to be transformed to an equivalent scheme with a stabilizing controller. Thus a question arises, if it is not simpler to deal in the design directly with structures appropriate for implementation.

Then, there exist also several other points that might be considered for a change. Firstly, the primary control loop is used to produced dynamical feedforward for the setpoint following. This is determined for a disturbance-free plant model. Hence, the integral action in the primary loop is excessive, or even harmful: it requires an additional anti-windup, an additional controller parameter tuning (integral time constant) and special tuning formulas for each type of plants (stable, integral and unstable (Normey-Rico and Camacho, 2009; Normey-Rico et al., 2009)). On the other hand, the primary loop based on a simple 2DOF P controller (Huba and Ťapák, 2011, 2012) may yield the same primary loop dynamics by using the only one tuning formula for all situations and an easy extension to cope with all the saturation problems.

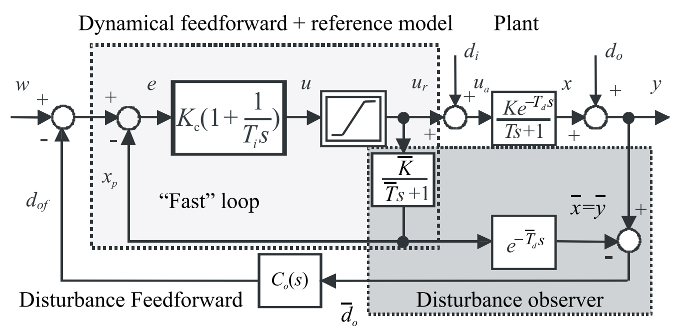

Fig. 1. 2DOF Smith predictor as an IMC structure with an output disturbance feedforward modifying input of the primary loop acting as a setpoint feedforward

Secondly, new solutions may be derived both for the input and output disturbances (Huba et al., 2016) and use higher order low pass filters. Within a linear framework, a distinction among the input and output disturbances is not important. The question is, if such an equivalence of different solutions holds also for real disturbances of a considered plant. Thirdly, consideration of both input and output disturbances enables to show relations between two (or even three) separately evolving approaches known as an internal model control (IMC), disturbance observer based control (DOC) and reference model control (RMC).

This paper may be considered as an experimental extension of Huba et al. (2016). After introducing the control problem in Section 2 and the IMC DTC in Section 3 it gives a short introduction to RMC in Section 4. Then, the thermal channel of the laboratory plant TOM1A is briefly introduced in Section 5, together with the main

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experimental results which are then discussed in Section 6 and summarized by Conclusions.

2. FOTD PLANT'S CONTROL

In application of the considered control design the attention is paid to the first order time delayed (FOTD) plant

$$S(s) = \frac{Y(s)}{U(s)} = \frac{K_s e^{-T_d s}}{s+a} \tag{1}$$

For quantifying the control speed, the IAE (Integral of Absolute Error) is going to be used defined as

$$IAE = \int_0^\infty |e(t)|\, dt \; ; \; e = w - y \tag{2}$$

Another important property, the output deviations from monotonicity (MO) may be evaluated by the TV_0 measure (relative total variance modified from TV introduced by Skogestad (2003))

$$TV_0(y) = \sum_i |y_{i+1} - y_i| - |y_\infty - y_0| \tag{3}$$

For a sufficiently fast control of the first order plants a MO output step response is always related to a one-pulse (1P) input consisting of two MO intervals separated by an extreme point, or an extreme interval. For stable plants a MO output may also be achieved by MO input, but such transients are usually much slower.

The plant input deviations from a 1P behavior may be evaluated in terms of

$$TV_1(u) = \sum_i |u_{i+1} - u_i| - |2u_m - u_\infty - u_0| \tag{4}$$

Thereby, u_0 and u_∞ represent the initial and final input values and $u_m \notin (u_0, u_\infty)$ is the extreme control value. Similarly, deviations of the output disturbance step responses from 1P shapes may be evaluated by $TV_1(y)$ measure. In control of FOTD systems a MO output step responses may also be combined with a higher number of input pulses, but the performance is still dominated by the above mentioned situations.

For responses with zero deviations from ideal shapes the corresponding IAE values may be calculated the the Laplace transform as integral error $IE = E(0)$;

3. IMC: MODIFIED 2DOF SMITH PREDICTOR (SP)

One of the first DTCs has been proposed by Smith (1957). Numerous solutions added an additional degree of freedom by choice of the feedback filter - the disturbance feedforward C_o (Fig.1) (Normey-Rico and Camacho, 2009; Normey-Rico et al., 2009). They have been primarily developed for stable FOTD plants [1]

$$S(s) = \frac{K e^{-T_d s}}{Ts+1} \; ; \; T = \frac{1}{a} \; ; \; K = \frac{K_s}{a} \tag{5}$$

with a primary PI controller

$$R(s) = K_c \frac{1 + T_i s}{T_i s}; \; T_i = \overline{T}; \; K_c = \frac{\overline{T}}{T_f \overline{K}} \tag{6}$$

This may be tuned to get a closed loop time constant T_f, which results into a dynamical feedforward

$$R_{ff}(s) = \frac{U(s)}{E(s)} = \frac{1}{\overline{K}} \frac{1 + \overline{T}s}{1 + T_f s} \tag{7}$$

The nominal setpoint-to-output transfer function

$$F_{wy}(s) = \frac{Y(s)}{W(s)} = R_{ff}(s) S(s) = Q_s(s) = \frac{e^{-T_d s}}{1 + T_f s} \tag{8}$$

does not include the dead time in the denominator and

$$IAE_s = T_d + T_f \tag{9}$$

For a setpoint feedforward filter $Q_s(s)$ an *output disturbance feedforward* may be chosen as

$$C_o(s) = Q_o(s)/Q_s(s) \tag{10}$$

The relative degree of the disturbance compensation filter $Q_o(s)$ must not be lower than the relative degree of $Q_s(s)$. Its dynamics may e.g. be chosen faster than that for the setpoint response, or, to annihilate the plant mode $s = -a = -1/T$ initiated by possible input disturbances. In choice of a generalized disturbance feedforward C_o [2]

$$C_o(s) = (1 + \beta_n s) Q_n \tag{11}$$

$$Q_n(s) = 1/(1 + T_f s)^n; \; n \geq 1 \tag{12}$$

one may follow the aim to eliminate the plant time constant T from the input disturbance responses $Y(s) = F_{iy}(s) D_i(s)$. This may be achieved by fulfilling

$$F_{iy}(0) = 0; \; F_{iy}(-1/T) = 0 \tag{13}$$

In the nominal case one gets

$$\beta_n = T\left[1 - (1 - T_f/T)^{n+1} e^{-T_d/T}\right] \tag{14}$$

The corresponding transfer functions and IE values are

$$\begin{aligned} F_{iy}(s) &= S(s)\left[1 - \frac{(1+\beta s)e^{-T_d s}}{(1+T_f s)^{n+1}}\right] \\ F_{oy}(s) &= 1 - \frac{(1+\beta s)e^{-T_d s}}{(1+T_f s)^{n+1}} \end{aligned} \tag{15}$$

$$\begin{aligned} IE_i(s) &= K[(n+1)T_f + T_d - \beta_n] \\ IE_o(s) &= (n+1)T_f + T_d - \beta_n \end{aligned} \tag{16}$$

Formally, the whole structure is equivalent to a loop with a traditional controller

$$R'(s) = R_{ff}(s)/[1 - R_{ff}(s)\overline{S}(s)C_o(s)] \tag{17}$$

This may also be useful in control design of unstable plants. It is, however, misleading to say that the Smith predictor may be used for such situations, since its internal signals would grow beyond all limits. Therefore, we are going to deal with structures that may directly be applied to unstable plants. Due to the properties of Diophantine equation (Kucera, 1993) they may guarantee the same input-output relations as the Smith predictor, but it is not correct to denote them by this name.

4. REFERENCE MODEL CONTROL (RMC)

An alternative reference model based methodology will be based on the loop with a stabilizing controller R for the FOTD plant augmented by setpoint and disturbance feedforwards and the corresponding reference models communicating to the stabilizing controller information about

[1] symbols with the bar correspond to estimates of real signals and parameter values

[2] Normey-Rico and Camacho (2008) required the relative degree of C_o to be the same as that of the considered plant; Here, also higher relative degrees will be considered imposed by chosen Q_n