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ABSTRACT

The presence of time delays in a continuous time system makes the control synthesis considerably more difficult. A simple dead-time compensation scheme has been proposed by Smith [1,2]. An analysis of this compensation scheme reveals that the open loop poles appear as internal modes in the conventional implementation. Other implementations which overcome this difficulty are proposed. These implementations can be regarded as different feedback realizations of the original scheme.

1. INTRODUCTION

In process control, time delays often appear as a pure dead time, e.g. in an actuator. The considerable phase retardation caused by the dead time makes it difficult to satisfy the requirements of insensitivity and accuracy using conventional techniques. A simple dead time compensation scheme was suggested by Smith[1,2], the so called Otto Smith regulator. Since the deadtime compensation scheme is easy to implement digitally, it is now finding increasing use in process control.

The regulator proposed by Smith is shown in the block diagram below.

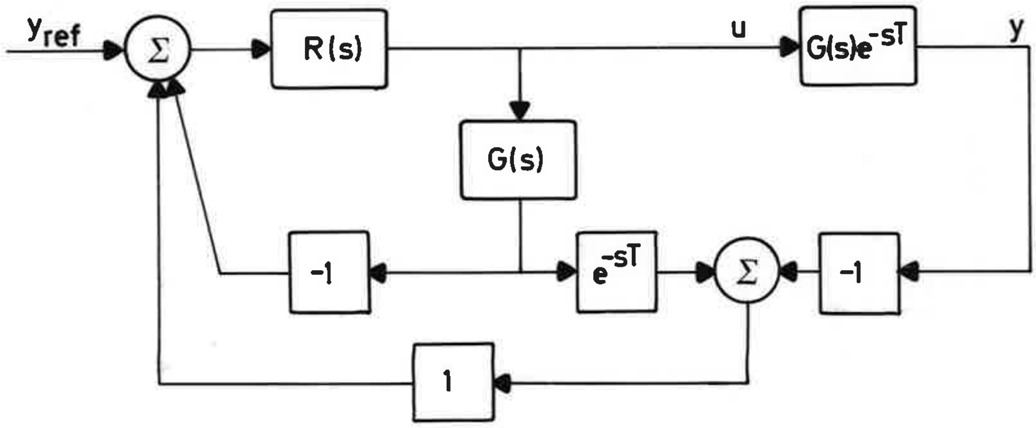


Fig. 1 The regulator proposed by Smith.

An internal analysis of this regulator is performed in this note. It is shown that, with the implementation above, the open loop poles of the plant appear as internal modes in the feedback system. Other implementations are then suggested which are insensitive internally. These implementations yield the same control signal u and the same output signal y for all exogenous signals y_{ref} but are stable internally. In other words, they are internally stable feedback realizations of the same external control scheme according to the terminology used in [4]. We also suggest a compensation scheme where internal insensitivity is taken into account.

2. THE DEAD TIME COMPENSATION SCHEME

Internal stability

Instead of considering the Otto Smith regulator directly, let us analyze the following more general scheme

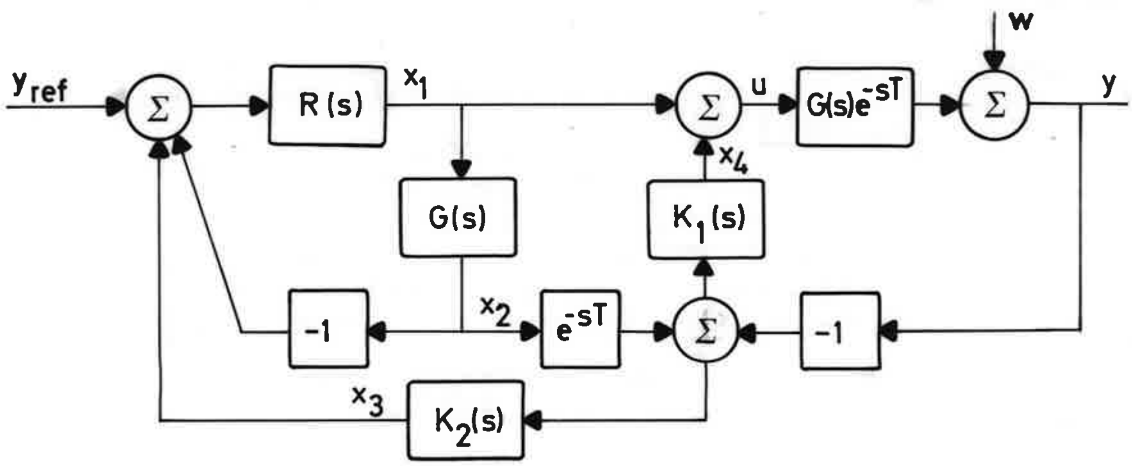


Fig. 2 A dead time compensation scheme.

The conventional regulator shown in Fig.1 is obtained as a special case by setting $K_1(s) = 0$ and $K_2(s) = 1$. The closed loop transfer functions in Fig.2 are straightforwardly computed to be (w is assumed to be zero)

$$y(s) = \frac{G(s)R(s)}{1 + G(s)R(s)} e^{-sT} y_{ref}(s) \tag{2.1}$$

and

$$u(s) = \frac{R(s)}{1 + G(s)R(s)} y_{ref}(s) \tag{2.2}$$

Note that both (2.1) and (2.2) are independent of the choice of $K_1(s)$ and $K_2(s)$. Therefore, we may regard the more general scheme in Fig.2 as an alternative way of implementing the conventional regulator shown in fig. 1 in the form of differential equations. The extra freedom provided by $K_1(s)$ and $K_2(s)$ can be used to give the regulator nice internal properties as is shown below.

From (2.1) we see the advantage of the compensation scheme used by Smith. The regulator R(s) can be synthezised as though the dead time is not present and then be implemented via the scheme in Fig.1 to provide some feedback. See [1,3] for more discussion on this point.

To perform an internal analysis, it is necessary to represent the feedback system in an internal form. Here, the operator form

$$Q(s)z(s) = P(s)u(s) \tag{2.3}$$

is used with suitable matrices Q(s) and P(s) and internal variables z(s). Introduce internal variables according to Fig.2 as

$$z = (x_1, x_2, x_3, x_4, y)^T$$

and let

$$G(s) = \frac{q(s)}{p(s)} \quad ; \quad R(s) = \frac{n(s)}{d(s)}$$

$$K_1(s) = \frac{n_1(s)}{d_1(s)} \quad ; \quad K_2(s) = \frac{n_2(s)}{d_2(s)} \tag{2.4}$$

The feedback system in Fig.2 is then represented by (2.3) where

$$Q(s) = \begin{bmatrix} d(s) & n(s) & -n(s) & 0 & 0 \\ -q(s) & p(s) & 0 & 0 & 0 \\ 0 & -n_2(s)e^{-sT} & d_2(s) & 0 & n_2(s) \\ 0 & -n_1(s)e^{-sT} & 0 & d_1(s) & n_1(s) \\ -q(s)e^{-sT} & 0 & 0 & -q(s)e^{-sT} & p(s) \end{bmatrix}$$

(2.5)

$$P(s) = \begin{bmatrix} n(s) \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The characteristic polynomial determining the internal modes of the closed loop system is now given by

$$\begin{aligned} d_c(s) &= \det Q(s) \\ &= d_2(s)(d_1(s)p(s) + n_1(s)q(s)e^{-sT})(d(s)p(s) + n(s)q(s)) \end{aligned} \tag{2.6}$$

In the conventional Otto Smith regulator $K_1(s) = 0$ and $K_2(s) = 1$, and therefore the characteristic polynomial becomes in this case

$$\hat{d}_c(s) = p(s)(d(s)p(s) + n(s)q(s)) \tag{2.7}$$

In (2.7), the first factor is the ch. p. for the open loop plant and the second the ch.p. for the closed loop transfer function (2.1) assuming no cancellation between G(s) and R(s). The open loop poles appear as internal modes of the conventional Otto Smith regulator which thus is sensitive to small perturbations or disturbances, especially if the open loop plant happens to be unstable.

Insensitive Implementations

By suitable choices of $K_1(s)$ and $K_2(s)$ it is possible to find an implementation which also has nice stability properties internally. In the ch.p. (2.6) the first factor depends exclusively on $K_2(s)$, the second on $K_1(s)$ and the third on R(s). Assuming no cancellations, the internal modes are thus the poles of the transfer functions

$$K_2(s) \quad ; \quad \frac{1}{1 + K_1(s)G(s)e^{-sT}} \quad ; \quad \frac{G(s)R(s)}{1 + G(s)R(s)} \tag{2.8}$$

From this we see that the compensators can be synthesized independently using conventional techniques, e.g. Nyquist plots. The role of $K_2(s)$ can be seen by introducing a disturbance w according to Fig.2. The closed loop transfer function becomes

$$y(s) = \frac{\left(1 - K_2(s)\dfrac{G(s)R(s)e^{-sT}}{1 + G(s)R(s)}\right)}{(1 + K_1(s)G(s)e^{-sT})} w(s) + \frac{G(s)R(s)e^{-sT}}{(1 + G(s)R(s))} y_{ref}(s) \tag{2.9}$$

Since $K_2(s)$ must be chosen stable, there is no steady state error in y for step disturbances w if

$$K_2(0) = \lim_{s \to 0} \frac{G(s)R(s) + 1}{G(s)R(s)} \tag{2.10}$$

and no steady state error in y for step inputs y_{ref} if

$$\lim_{s \to 0} \frac{G(s)R(s)}{1 + G(s)R(s)} = 1$$

A similar analysis can be done for ramp inputs on w and y_{ref} which give further conditions on $K_2(s)$ and R(s). Since the analysis is straightforward it is omitted here. By (2.10) we conclude that $K_2(s)$ can be used to provide satisfactory steady state regulation for disturbances.

The following dead time compensation scheme summarizes the discussions made above.

(1) Synthesize R(s) as though the dead time is not present using conventional techniques.

(2) Choose $K_2(s)$ stable and such that satisfactory steady state response is obtained, cf. (2.10).

(3) Choose $K_1(s)$ such that sufficient internal stability is achieved, cf. (2.9), using e.g. Nyquist plots.

(4) Implement the regulator via the scheme in Fig.2.

The only step where the dead time appears is in step 3. If the open loop plant is stable, it is possible to choose $K_1(s) = 0$ for stability, but to have some internal stability it is advisable to choose $K_1(s) \neq 0$, especially since the transient response for disturbances depends on $K_1(s)$, cf. (2.9). Some of the simplicity of the original compensation scheme is lost by step 3, but since the accuracy for reference inputs is determined by R(s) and the steady regulation of disturbances by $K_2(s)$, $K_1(s)$ can be chosen to achieve internal stability without bothering about response for reference inputs or steady state errors. The compensation scheme is demonstrated in the following example.

Example

Consider a plant described by the following transfer function

$$G(s) = \frac{1}{s^2+0.2s+1} e^{-sT} \quad ; \qquad T = 0.5 \qquad (2.11)$$

A satisfactory regulator for this system (disregarding the timedelay) is a PID-regulator

$$R(s) = 5 + \frac{1}{0.5s} + \frac{3s}{1+0.1s}$$

The step response for the conventional Otto Smith regulator is shown in fig. 3(a). The closed loop system is sensitive. This is demonstrated in fig. 3(b) where a step disturbance of 0.3 is added to the plant input.

To overcome this difficulty, we use the suggested scheme. To have zero steady state error for steps inputs we take

$$K_2(s) = \lim_{s\to 0} \frac{G(s)R(s) + 1}{G(s)R(s)} = 1$$

e.g.

$$K_2(s) = 1.$$

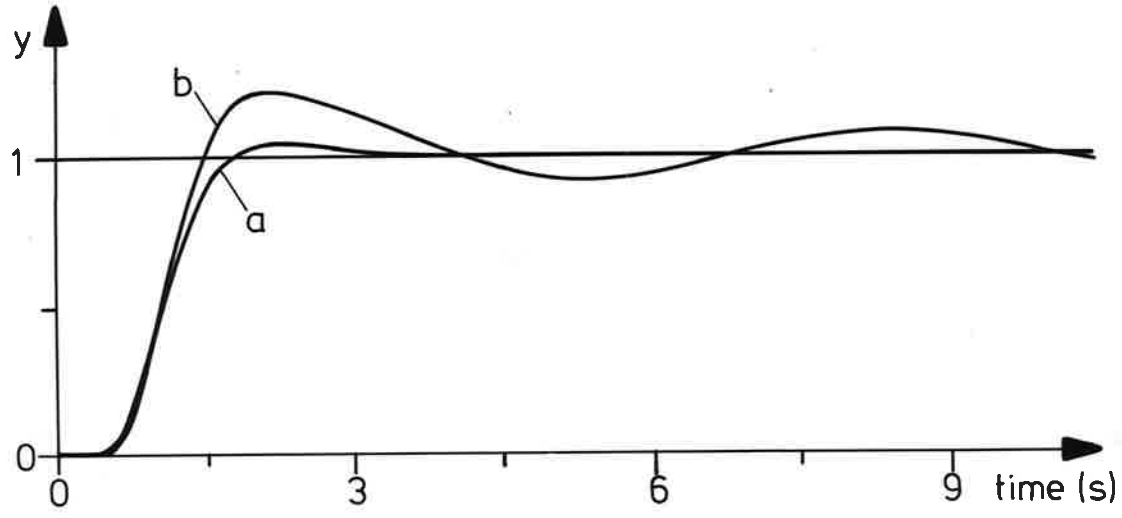
Moreover, to have internal stability, choose $K_1(s)$ such that the transfer function

$$\frac{1}{1 + K_1(s)G(s)e^{-sT}}$$

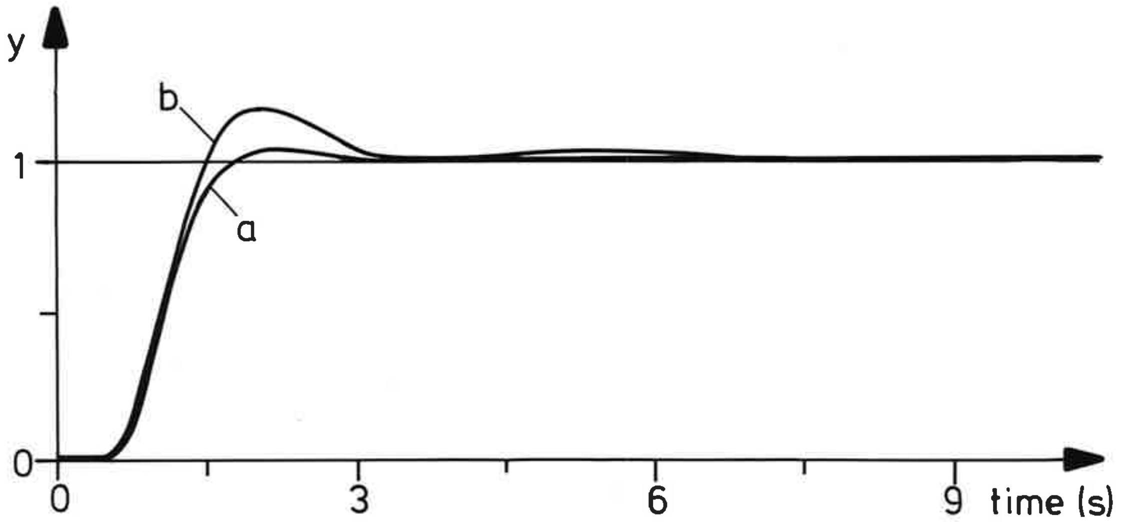
has a satisfactory degree of stability. This is achieved if $K_1(s)$ is chosen to be a PID-regulator

$$K_1(s) = 0.1 + \frac{0.8s}{1+0.08s}$$

The step response for the regulator in fig. 2 becomes now as in fig. 4(a). If the same perturbation as above is made, the step response becomes as in fig 4(b), i.e. the sensitivity of the conventional implementation is avoided.



<u>Fig. 3</u> Step response for the conventional Otto Smith regulator, (a) unperturbed (b) perturbed



<u>Fig. 4</u> Step response for modified Otto Smith regulator, (a) unperturbed (b) perturbed

References

1. Smith O.J.M. "Closer control of loops with dead time" Chem.Eng.Progress 53 (1957) 217-219.

2. Smith O.J.M. "Feedback control systems" Mc Graw Hill, New York (1958).

3. Åström K.J. "Frequency domain properties of Otto Smith regulators" Int. J.Control Vol. 26 no. 2, 307-314 (1977).

4. Bengtsson G. "Feedback realizations in linear multivariable systems", IEEE Trans. Autom. Control, vol. AC - 22 no. 4, 576-585 (1977).