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Performance indices for feedforward control

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ABSTRACT

In this paper, a performance benchmark for the assessment of two feedforward control architectures for the load disturbance compensation problem is proposed. In particular, two indices are devised so that the advantage of using a feedforward compensator with respect to the use of a feedback controller only is quantified. Furthermore, these metrics will help to make quantitative comparisons among different feedforward control schemes and tuning rules. Analysis and simulation results are given to demonstrate the effectiveness of the proposed approach.

1. Introduction

In process control, it is well-known that the addition of a feedforward control action to a standard feedback control scheme improves the compensation of measurable disturbances acting on a process [1–4], provided that the model of the process and the model of the disturbances are known with a sufficient accuracy [5–7]. Ideally, the effects of the disturbance on the process output can be compensated by applying a control action that gives a response equal (but with an inverse sign) of that provided by the disturbance. However, this is not always possible, as the ideal feedforward compensator, which is typically calculated by multiplying the load disturbance transfer function by the inverse of the process transfer function, may not be realizable as it can be non causal or unstable [8].

In this context, a few methodologies have been proposed in the literature for the design of the feedforward compensator. In [9], the feedforward block is optimized, by taking also the feedback controller into account, in order to minimize a weighted norm of the transfer function from the disturbance to the process output. In [10], the robustness of the controller is addressed explicitly by considering a generalization of the Internal Model Control approach. In [11], simple tuning rules have been developed in order to minimize the Integrated Absolute Error (*IAE*) by taking also the action by the feedback controller into account. These simple tuning rules have recently been generalized in [12] for the non-realizable delay inversion problem. In [13], simple tuning rules based on minimization of the Integrated Squared Error (*ISE*) were also derived.

Adding feedforward control to the feedback controller, an improvement of the performance is expected. By also taking the additional effort for the feedforward controller implementation into account, it is interesting to quantify the improvement of the performance that can be achieved by adding the feedforward compensator. In this topic, in [14], it was highlighted that it is worth employing a feedforward action if the disturbance enters close to the input of the process, while if the disturbance enters late in the process, the expected improvement is small. In this context, a simple method to assess if a feedforward action is worth to be used was proposed.

In this paper we present a performance index in order to evaluate the benefit of a feedforward controller with respect to the use of just a simple feedback Proportional-Integral-Derivative (PID) controller. Two feedforward control architectures are considered. The first one is the most typically employed in practical cases and consists of a lead-lag controller [7]. The second one [15] is a little bit more complex and, with respect to the previous one, implies the addition of one block in the control scheme in order to (ideally) annihilate the contribution of the feedback controller. Quantitative comparisons between these two control schemes and among different tuning rules are also presented. The determined values of the

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performance index are based on simple assumptions, like the use of first-order-plus-dead-time (FOPDT) models for the process and load disturbance transfer functions, which are in any case reasonable in practical cases. On the other hand, the lambda tuning rule is used as tuning method for the PID controller.

The paper is organized as follows. In Section 2, the basics of feedforward control for disturbance compensation is briefly reviewed and the two feedforward control schemes considered in the paper are outlined. The performance index is defined and calculated in Section 3. An analysis and discussion of the improvement in performance that can be achieved using the feedforward control schemes is provided in Section 4. Afterwards, Section 5 is devoted to present some numerical examples. Finally, conclusions are drawn in Section 6.

2. Feedforward control

The standard feedforward control scheme for disturbance compensation is shown in Fig. 1, where $P(s)$ is the process transfer function, $H(s)$ is the disturbance transfer function, $G(s)$ is the feedforward compensator, and $C(s)$ is the transfer function of a PI controller:

$$C(s) = K_p\left(1 + \frac{1}{sT_i}\right), \tag{1}$$

where K_p is the proportional gain and T_i is the integral time constant. Hereafter we assume that the (self-regulating) process can be modeled effectively by a FOPDT transfer function and this applies also to the disturbance transfer function that models the influence of the disturbance d on the process output y. On the other hand, the PI controller will be tuned according to the well-known lambda tuning rule.

Thus, we have

$$P(s) = \frac{K}{Ts+1}e^{-Ls} \tag{2}$$

and

$$H(s) = \frac{\mu}{\tau s+1}e^{-\theta s}, \tag{3}$$

where K and μ are the static gains, $T > 0$ and $\tau > 0$ (in this work only the stable case is analyzed) the time constants, and L and θ the time delays, respectively. Note that a methodology for the estimation of the process and disturbance transfer function parameters based on the evaluation of routine operating data has been proposed in [16].

The feedforward block, $G(s)$, is given by a classical lead-lag compensator with time delay

$$G(s) = K_{ff}\frac{T_z s+1}{T_p s+1}e^{-L_{ff}s}. \tag{4}$$

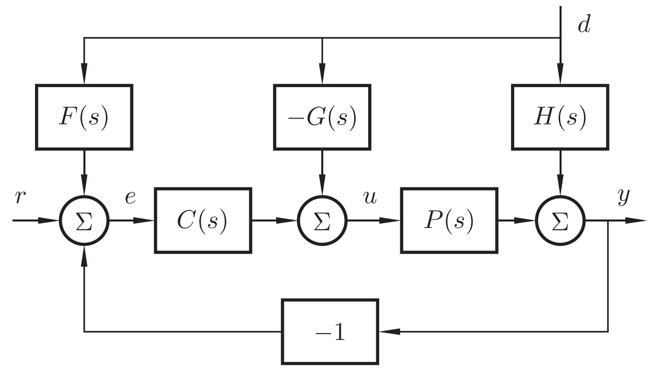

Fig. 2. Non-interacting feedforward control scheme.

In theory, if the disturbance is measurable, the transfer function from d to y can be set to zero by using the block $G(s)$ determined as

$$G(s) = \frac{\mu}{K}\frac{Ts+1}{\tau s+1}e^{(L-\theta)s}. \tag{5}$$

It appears that if $L \le \theta$, block G is realizable and a perfect compensation can be achieved. On the contrary, if $L > \theta$ the block $G(s)$ is non causal and cannot be realized, and therefore a perfect compensation is not possible. The typical approach in this case is to just neglect the dead-times of P and H, resulting in the following feedforward compensator

$$G(s) = \frac{\mu}{K}\frac{Ts+1}{\tau s+1}. \tag{6}$$

As perfect compensation is not possible in this case, it is therefore interesting to evaluate the increment of the performance that nevertheless can be achieved by using approximated feedforward controller (6) in the control scheme of Fig. 1 with respect to the use of just the feedback controller (1) (that is, $G(s) = 0$). Notice also that the feedforward design based on (6) is done in open-loop, but the performance is then evaluated in closed-loop, where the feedback has a negative influence in the load rejection response such as discussed in [11]. This fact is also an interesting issue to be analyzed.

An alternative control scheme, which allows the separation of the design of the feedforward and feedback control scheme and thus removing the feedback influence, is that proposed in [15] and shown in Fig. 2. In this non-interacting feedforward control scheme, a feedforward from disturbance d is not only added to the controller output, but also to its input through transfer function $F(s)$. In this case, the feedback control error, e, is given by the following expression:

$$e = r + Fd - y = \frac{r + (F - H + PG)\,d}{1 + CP}, \tag{7}$$

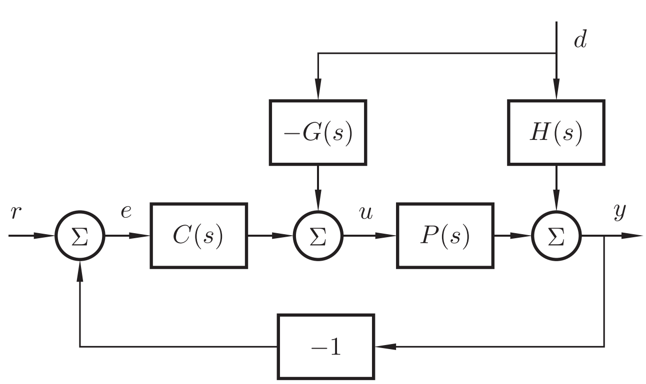

Fig. 1. Classical feedforward control scheme.