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Optimal feedforward compensators for systems with right-half plane zeros

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ABSTRACT

Feedforward from measurable disturbances is a powerful complement to feedback control to improve disturbance rejection capability. Recent works have remarked the necessity of a design strategy for those cases where the ideal feedforward controller is not realizable. In this paper, a simple shaping design procedure is presented together with straightforward rules to obtain optimal feedforward controllers for the case when the ideal compensator is not realizable due to right-half plane zeros in the process dynamics. Finally, some simulations and a robustness analysis demonstrate the benefits of the proposed tuning rules.

1. Introduction

Measurable disturbance compensation through feedforward control structures is a well-known strategy in process control to improve classic feedback performance [1,2]. However, the realizability conditions of the ideal feedforward controller are rarely studied and therefore there are only a few rules to deal with these scenarios.

The ideal feedforward compensator within a classic feedforward scheme is formed as the quotient of the reversed sign dynamics between the load disturbance and the process output divided by the dynamics between the control signal and the process output. Since a process inverse function is needed, this controller may not be realizable. These cases are: non-realizable delay inversion, RHP (right-half plane) zeros, integrating poles, or improper transfer function [2,3].

In [4], it was demonstrated that if the perfect feedforward controller is not applied, a residual effect from the disturbance is fed back to the feedback controller which, if ignored, greatly deteriorates the performance. To counteract this effect, a non-interacting feedforward structure was also proposed. This scheme highly simplifies feedforward compensator design as an independent nominal analysis can be developed for both reference tracking and disturbance rejection, even if the ideal compensator is not realizable.

Lately, tuning rules for feedforward compensators in those cases where the perfect controller is not realizable have appeared within classic and non-interacting feedforward control schemes. In particular, the problem of non-realizable delay inversion was treated in [5], where a design based on the minimization of integral absolute error and the reduction of the undershoot in the response were proposed. This rule was later complemented [6,7] for the non-interacting scheme and a final tuning guideline was presented to handle the problem of delay inversion.

Within an internal model control structure, a different approach for, initially stable systems [8], and later for unstable processes [9], were proposed. In these works, the authors establish a general design framework, in which a robust tuning procedure is used. However, this control structure, as well as those with feedforward made from the reference, requires a different design and are not treated in this work.

The main objective of this work is to obtain a straightforward guideline to design optimal feedforward compensators for systems with RHP zeros. As a result, three simple tuning rules for non-interacting feedforward controllers affected by step-like disturbances are derived to obtain a desired settling time, or to minimize H_∞ or H_2 norms, respectively.

The paper is organized as follows. A brief overview of the non-interacting feedforward scheme including closed-loop relationships is presented in Section 2. Section 3 introduces the

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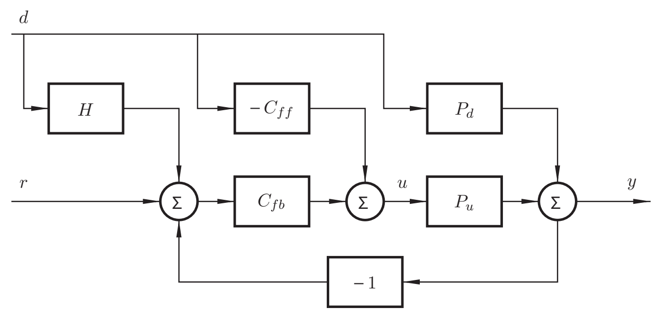

Fig. 1. Block diagram illustrating the non-interacting feedforward control scheme.

proposed feedforward structure for shaping the disturbance rejection response. Furthermore, three simple rules to define the desired temporal response are obtained. In Section 4, the proposed design is tested with some simulations and robustness analysis. Finally, Section 5 conducts the conclusions of the work.

2. Feedforward from disturbances

In this section, the non-interacting feedforward control structure presented in [4] is briefly described. The main advantage of this scheme is that it makes an independent analysis and design for reference tracking with the feedback controller and disturbance rejection with the feedforward compensator possible, as stated in [6,7].

Fig. 1 presents the non-interacting feedforward block diagram. There are two processes P_u and P_d relating the process output y to the control signal u and the measurable disturbance d, respectively. A primary controller C_{fb} is used within a classic closed-loop system to guarantee reference tracking in spite of model uncertainties and measurement noise. Moreover, the feedforward compensator C_{ff} is connected in open-loop to counteract measurable disturbance effects. Finally, a block H is introduced to totally remove the effect of the measurable disturbance from the primary control loop. This structure is a generalization of the classical feedforward scheme (which has $H = 0$).

The relationships for reference tracking and disturbance rejection with this scheme are

$$\frac{y(s)}{r(s)} = \frac{L(s)}{1+L(s)} = \eta(s) \tag{1}$$

$$\frac{y(s)}{d(s)} = \frac{P_{ff}(s)}{1+L(s)} + \frac{L(s)H(s)}{1+L(s)} = P_{ff}(s)\varepsilon(s) + H(s)\eta(s) \tag{2}$$

where $\varepsilon(s)$ and $\eta(s)$ are the sensitivity and complementary sensitivity transfer functions, respectively, such that $\varepsilon(s)+\eta(s)=1$, $L(s)=C_{fb}(s)P_u(s)$ is the open-loop direct chain, and $P_{ff}(s)=P_d(s)-C_{ff}(s)P_u(s)$ is the open-loop disturbance rejection.

Note that in a classic feedforward scheme – with $H=0$ – perfect disturbance rejection is achieved for $C_{ff}(s)=P_d(s)/P_u(s)$. However, when the ideal compensator is not realizable, an interaction between $C_{fb}(s)$ and $C_{ff}(s)$ arises since $P_{ff} \neq 0$. Within the non-interacting feedforward scheme, it is possible to make $C_{fb}(s)$ independent of d by choosing $H(s)=P_{ff}(s)$ such that

$$\frac{y(s)}{d(s)} = P_{ff}(s)(\varepsilon(s)+\eta(s)) = P_{ff}(s). \tag{3}$$

In what follows, the special case of non-realizable feedforward compensators for RHP zeros is presented, and a procedure to shape the desired response is derived. First, a tuning rule to obtain a desired settling time is obtained. Afterwards, two simple tuning rules based on the minimization of the H_2 and H_∞ norms are proposed.

3. Design of feedforward compensator

3.1. The problem of non-minimum phase zero

The commented problem appears when inverting process $P_u(s)$ with RHP zeros, since it results in unstable poles in $C_{ff}(s)$. Let us consider the following process descriptions

$$P_u(s) = \frac{\kappa_u(-\beta_u s+1)}{D_u^-(s)} e^{-\lambda_u s} \quad \beta_u > 0, \tag{4}$$

$$P_d(s) = \frac{\kappa_d}{D_d^-(s)} e^{-\lambda_d s} \tag{5}$$

such that $\lambda_u \le \lambda_d$, $s=1/\beta_u$ is a zero in the right-half plane, and $D_u^-(s) = 1+\sum_{i=1}^{n_u} a_u[i]s^i$ and $D_d^-(s) = 1+\sum_{i=1}^{n_d} a_d[i]s^i$ are polynomials with n_u and n_d degree, respectively, such that all their roots are located in the LHP (left-half plane). Note that it is supposed without any loss of generality that $D_u^-(0)=D_d^-(0)=1$ to ensure that κ_u and κ_d are the process static gains. Note that it is considered that no unstable poles exist in the system since the non-interacting feedforward would result in an internally unstable controller.

If the disturbance rejection problem is studied in this case, it is obtained that

$$\frac{y(s)}{d(s)} = e^{-\lambda_d s}\left(\frac{\kappa_d}{D_d^-(s)} - C_{ff}(s)\frac{\kappa_u(-\beta_u s+1)}{D_u^-(s)} e^{-(\lambda_u-\lambda_d)s}\right). \tag{6}$$

This problem is typically treated in the literature by defining the feedforward compensator $C_{ff}(s)$ just as a gain or a lead-lag filter. Sometimes, a delay is also needed to ensure that the compensation is not made too early. Hereafter, a methodology to design the feedforward compensator to shape (6) is proposed.

3.2. Feedforward compensator structure

This section presents a proposal for the feedforward controller transfer function in order to compensate the RHP zeros and to obtain an undershoot-free response for the load disturbance rejection problem. To this end, the feedforward compensator is defined as

$$C_{ff}(s) = \frac{\kappa_d}{\kappa_u}\cdot\frac{D_u^-(s)}{D_d^-(s)}\cdot\frac{(1+\sum_{i=1}^{m_{ff}}\beta_{ff}[i]s^i)}{(\tau_{ff}s+1)^{n_{ff}}} e^{-(\lambda_d-\lambda_u)s}. \tag{7}$$

where $\beta_{ff}[i]$ and τ_{ff} are the coefficients to be tuned.

Remember that the feedforward controller time delay is realizable since $\lambda_u \le \lambda_d$. Otherwise, the ideas presented in [5,7] should be used.

Inserting the expression for $C_{ff}(s)$ in (7) in Eq. (6) gives

$$\frac{y(s)}{d(s)} = \frac{\kappa_d e^{-\lambda_d s}}{D_d^-(s)}\left(1 - \frac{(1+\sum_{i=1}^{m_{ff}}\beta_{ff}[i]s^i)(-\beta_u s+1)}{(\tau_{ff}s+1)^{n_{ff}}}\right). \tag{8}$$

The idea is to cancel all stable roots of $D_d^-(s)$ with $\beta_{ff}[i]$ coefficients, and therefore it is necessary to set $m_{ff}=n_d$. Furthermore, it is considered $n_{ff} \ge n_u$ to achieve a realizable compensator. Then, τ_{ff} is used as the only tuning parameter.

Using the binomial theorem, Eq. (8) can be reformulated as

$$\frac{y(s)}{d(s)} = \frac{\kappa_d P_0 s}{(\tau_{ff}s+1)^{n_u}}\cdot\frac{P(s)}{D_d^-(s)} e^{-\lambda_d s} \tag{9}$$

with

$$P_0 = n_u\tau_{ff} + \beta_u - \beta_{ff}[1] \tag{10}$$