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Optimal feedforward compensators for integrating plants ⋆

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Abstract: This paper addresses the design of feedforward compensators for integrating processes. Initially, the disturbance rejection problem for a classic two degrees-of-freedom control scheme with feedfoward is analyzed to highlight the problem caused by integrating dynamics. Afterwards, two simple tuning rules are derived to obtain undershoot-free responses based only a desired settling time or by satisfying a tradeoff between maximum peak and settling time specifications. Finally, some simulations are shown to prove the advantages of the proposed controller. © *Copyright IFAC 2014*

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1. INTRODUCTION

Feedforwarding measurable disturbance signals to compensate their effects before they affect the system is a classic strategy in process control [Hägglund, 2013]. Even though feedforward control is an old topic [Seborg et al., 2004], most existing tuning rules only consider the ideal cases or are only applied to very specific problems [Nisenfeld and Miyasak, 1973, Seborg et al., 2004].

The ideal feedforward compensator within a classic feedforward scheme is formed as the quotient of the reversed sign dynamics between the measurable disturbance and the process output divided by the dynamics between the control signal and the process output. However, in many cases this controller becomes non-realizable due to several causes: non-realizable delay inversion, non-minimum phase zeros, unstable poles, integrating dynamics or improper transfer function [Seborg et al., 2004, Guzmán et al., 2012].

In those cases where the perfect feedforward controller is not realizable, the effect of the measurable disturbance can not be totally rejected from feedback error using a classic feedforward scheme. In [Brosilow and Joseph, 2012], a non-interacting feedforward structure was introduced to cope with this problem by introducing a new block. This scheme greatly simplifies feedforward compensator design, as an independent nominal analysis can be done for both reference tracking and disturbance rejection even if the ideal compensator is not realizable. However, the main limitation of this scheme is that it cannot deal with unstable or integrating plants.

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Recently, feedforward controller tuning rules have appeared in the literature within classic and non-interacting feedforward schemes. [Guzmán and Hägglund, 2011] proposed a design based on the minimization of integral absolute error and the reduction of undershoot for the case when ideal feedforward is not realizable due to delay inversion problems. Similar results within a non-interacting feedforward scheme were also pointed in [Hast and Hägglund, 2012] and [Rodríguez et al., 2013], where the objective was the minimization of the integral squared error. All of these rules are based on simple first-order plus time delay systems, and their extension to higher-order dynamics is seldom achievable.

A different approach for stable systems is proposed in [Vilanova, 2007], where the authors establish a general design framework, in which a robust tuning procedure within an internal model control structure is used. This strategy was later extended to unstable processes in [Vilanova et al., 2009]. However, this control structure as well as those with feedforward made from the reference require a different design and are not treated in this work.

Within a classic feedforward scheme, a methodology to design feedforward compensators by shaping the disturbance rejection response for the case when ideal feedforward is not realizable due to plants with integrating dynamics is required. To suggest simple tuning rules for this case is the main contribution of this paper.

The paper is organized as follows. A brief overview of the classic feedforward scheme including closed-loop relationships is presented in section 2. Section 3 introduces the proposed design methodology for shaping the disturbance rejection response. Two simple rules to define the shape response according to settling time or as a tradeoff between maximum peak and settling time are obtained. In section

4, the proposed design is tested with some simulations. Finally, section 5 conducts the conclusions of the work.

2. CONTROL SCHEME

In this section, the classic feedforward control together with a two degrees-of-freedom (2DOF) structure is described. It is a well-known structure which allows to compensate measurable disturbance effect as soon as possible with an independent design for reference tracking and disturbance rejection. The main advantage with respect to classic feedback is that a control action is supplied even if there is no feedback error.

Fig. 1 presents the classic feedforward block diagram. There are two processes P_u and P_d relating the process output y with the control signal u and the measurable disturbance d, respectively. A primary controller C_{fb} and a reference filter F_r are used within a 2DOF closed-loop system for reference tracking purposes. Moreover, the feedforward compensator C_{ff} is connected in open-loop to counteract measurable disturbance effects.

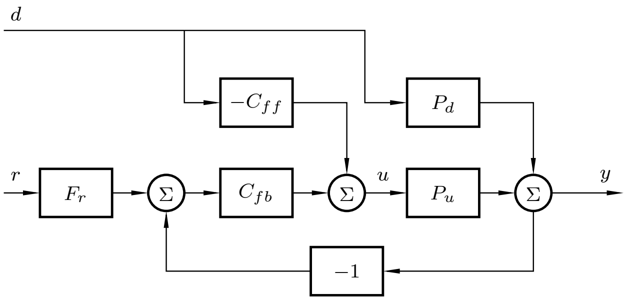

Fig. 1. Block diagram illustrating a 2DOF + feedforward control scheme

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

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

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

where $L(s) = C_{fb}(s)P_u(s)$ 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 chain.

Note that within this scheme, perfect disturbance rejection is achieved for $C_{ff}(s) = P_d(s)/P_u(s)$. However, when the ideal compensator is not realizable, it can be observed that an interaction between $C_{fb}(s)$ and $C_{ff}(s)$ arises [Guzmán and Hägglund, 2011, Guzmán et al., 2012].

In what follows, the special case of integrating plants is presented and a procedure for shaping the disturbance rejection response based on a desired settling time is derived. Furthermore, an optimal controller which finds a satisfying tradeoff between maximum peak and settling time is proposed.

3. FEEDFORWARD DESIGN

In this section, the problem of integrating processes is presented and the controller design approach is addressed. Let us consider the following process descriptions

$$P_u(s) = \frac{\kappa_u}{D_u(s)s^{t_u}} \tag{3}$$

$$P_d(s) = \frac{\kappa_d}{D_d^-(s)} \tag{4}$$

such that t_u is the type of process $P_u(s)$, $D_u(s) = 1 + \sum_{i=1}^{n_u} a_u[i]s^i$ is a polynomial of degree n_u and $D_d^-(s) = 1 + \sum_{i=1}^{n_d} a_d[i]s^i$ is a polynomial of degree n_d with all its roots in the left half plane (LHP). 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 process integrator and static gains, respectively.

As well-known, within a 2DOF control scheme, it is possible to shape the reference tracking response by correct tuning reference filter and feedback controller.

Let us consider

$$F_r(s) = \frac{1}{D_{fr}(s)} \tag{5}$$

$$C_{fb}(s) = \kappa_{fb}\frac{N_{fb}(s)}{D_{fb}(s)s^{t_{fb}}} \tag{6}$$

such that t_{fb} is the type of $C_{fb}(s)$ and $D_{fr}(0) = N_{fb}(0) = D_{fb}(0) = 1$ to ensure that 1 and κ_{fb} are $F_r(s)$ and $C_{fb}(s)$ static and integrator gains, respectively.

The reference tracking response can now be expressed as

$$\begin{aligned}\frac{y(s)}{r(s)} &= \frac{1}{D_{fr}(s)}\frac{N_{fb}(s)}{N_{fb}(s) + \frac{D_{fb}(s)D_u(s)s^{t_{fb}+t_u}}{\kappa_{fb}\kappa_u}} \\ &= \frac{1}{D_{fr}(s)}\frac{N_{fb}(s)}{D_{cl}(s)}\end{aligned} \tag{7}$$

where $D_{cl}(s)$ is a polynomial of degree n_{cl} that represents the closed-loop system dynamics. Note that since $D_{cl}(0) = 1$, if $t_{fb} + t_u \geq 1$, the reference tracking response has unitary static gain. In fact, to achieve zero steady-state error against reference signals with t_r poles in $s = 0$ ($r(s) = s^{-t_r}$), it is necessary to set $t_{fb} \geq t_r - t_u$.

Furthermore, if it is set $D_{fr}(s) = N_{fb}(s)$, the following final expression is obtained

$$\frac{y(s)}{r(s)} = \frac{1}{D_{cl}(s)} \tag{8}$$

Remember that since $D_{cl}(0) = 1$, expression (8) has unitary static gain.

3.1 Disturbance rejection

Within a classic feedforward scheme (see Fig. 1), it is possible to improve the disturbance rejection behaviour even if unstable dynamics exist in process $P_u(s)$. In fact, equation (2) can be expressed as

$$\begin{aligned}\frac{y(s)}{d(s)} &= \left(\frac{\kappa_d}{D_d^-(s)} - C_{ff}(s)\frac{\kappa_u}{D_u(s)}s^{-t_u}\right)\frac{D_u(s)s^{t_u}D_{fb}(s)s^{t_{fb}}}{D_{cl}(s)} \\ &= \left(\frac{\kappa_d D_u(s)s^{t_u}}{D_d^-(s)} - C_{ff}(s)\kappa_u\right)\frac{D_{fb}(s)s^{t_{fb}}}{D_{cl}(s)}\end{aligned} \tag{9}$$

where it can be observed that even unstable dynamics of $P_u(s)$ caused by its poles located in the right half