Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Design and performance assessment of setpoint feedforward controllers to break tradeoffs in univariate control loops

Zhenpeng Yu * **Jiandong Wang** *,[1] **Biao Huang** ** **Jun Li** *** **Zhenfu Bi** ***

* *College of Engineering, Peking University, Beijing, China 100871*
** *Dept. of Chemical & Materials Engr., University of Alberta, Edmonton, Canada T6G 2V4*
*** *Shandong Electric Power Research Institute, Jinan, China 250002*

Abstract: This paper studies the design and performance assessment of setpoint feedforward controllers in univariate control loops. A design method for the setpoint feedforward controller is proposed, aiming at breaking the two fundamental tradeoffs among the setpoint tracking, the load disturbance rejection and the robustness against model uncertainties. The lower bound for the total variation (TV) is established. An IAE-TV-based performance index is devised to assess the performance of the setpoint feedforward controller. The effectiveness of the proposed feedforward controller design method and the performance assessment method are illustrated by simulation and experimental examples.

Keywords: Setpoint feedforward control, performance assessment, total variation

1. INTRODUCTION

PID controllers undoubtedly play an important role in process industries. Design of PID controllers usually considers the mutually conflicting requirements on the responses to the setpoint and load disturbance variations, as well as on the robustness against model uncertainties (Aström and Hägglund, 2004). There are two well-known tradeoffs in a single feedback control loop. One tradeoff is between the performances in terms of setpoint tracking and load disturbance rejection (Araki, 2003; Visioli 2006a; Piccagli & Visioli, 2012; Arrieta, 2012). Another tradeoff is between the setpoint tracking performance and the robustness against model uncertainties (Hagglund, 2002; Alfaro, 2012).

To break the tradeoffs, a conventional approach is to adopt a two degrees-of-freedom controller, such as the setpoint filtering (Panagopoulos, 2002; Vijayan, 2012) or the setpoint weighted control scheme (see Alfaro *et al.* 2009 for the summary of these control schemes). The major drawback of them is that the setpoint response may be unnecessarily sluggish (Aström and Hägglund, 2005, Page 144), because the tradeoff between the performances in terms of setpoint tracking and load disturbance rejection is not completely broken. A feedback plus setpoint feedforward and filter control scheme was proposed by Aström and Hägglund (2005, Page 140), where three controllers are exploited. This control scheme has the potential to break the tradeoffs in a complete manner. However, an improper design of controllers may lead to a large fluctuation in the control signal (Visioli, 2006a, Page 94).

In recent two decades, controller performance assessment has been an active research topic. It studies the problems of how well a control loop meets with the control target and how to improve the performance if necessary (Jelali, 2006). For univariate feedback control loops, the celebrated minimum variance control (MVC) benchmark was introduced by Harris (1989), and was further developed by many researchers, e.g., Huang & Shah (1999), Ko & Edgar (1998, 2004), Jain & Lakshminarayanan (2005). As alternatives to the MVC benchmark, the idle index, the area index, the IAE-based index, the hurst index were respectively proposed by Hägglund (1999), Visioli (2006b), Veronesi & Visioli (2009), Yu *et al.* (2011, 2012) and Srinivasan *et al.* (2012), to assess the performances of univariate feedback control loops from different perspectives. For disturbance feedforward control loops, Petersson *et al.* (2003) and Olaleye *et al.* (2004) developed the performance indices based on the MVC benchmark. For cascaded control loops, Ko & Edgar (2000) developed a performance assessment method based on the MVC benchmark, and Veronesi & Visioli (2011) presented the IAE-based performance index. However, to our best knowledge, there has not appeared performance assessment methods for SetPoint Feedforward Plus Feedback (SPFF) control loops.

The main contribution of this paper is two-fold. First, A design method for setpoint feedforward controllers, is provided, for a SPFF control scheme depicted in Fig. 1, aiming at breaking the above-mentioned two tradeoffs in a complete manner. Second, the lower bound for the total variation (TV) of control signal is established, based on which, an IAE-TV-based performance index is proposed to assess the performance of setpoint feedforward controllers.

[1] Corresponding author: Telephone: +86 (10) 6275-3856; Email: jiandong@pku.edu.cn

The rest of the paper is organized as follows. Section 2 describes the problems to be solved. Section 3 provides a design method for controllers. Section 4 establishes the lower bounds of TV, based on which an index is proposed to assess the performance of the setpoint feedforward controller. Sections 5 and 6 provide numerical and experimental examples for illustration of the obtained results. Section 7 concludes the paper.

2. PROBLEM FORMULATION

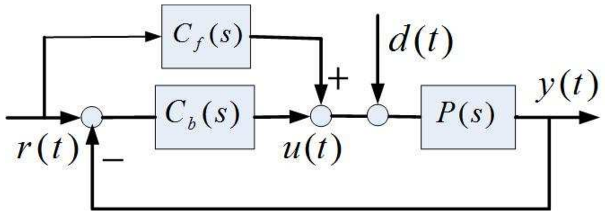

Fig. 1. The SPFF control loop

Consider a SPFF control scheme depicted in Fig. 1. Here $P(s)$, $C_b(s)$ and $C_f(s)$ are the process, the feedback controller and the setpoint feedforward controller, respectively; $r(t)$, $d(t)$, $u(t)$ and $y(t)$ are the setpoint, the input load disturbance, the control signal, and the process output, respectively.

The following conditions are assumed to hold:

A1. The process $P(s)$ is confined to be a linear time-invariant (LTI) process that is stable, without integrals and negative zeros, and can be well described by an FOPDT model (Serbog *et al.*, 2004),

$$P(s) \approx \frac{Ke^{-\theta s}}{\tau s+1}. \tag{1}$$

In this context, it is assumed that $P(s)$ is known as *priori*. It is stressed that the modeling problem is out of scope here.

A2. The feedback controller $C_b(s)$ takes a series PI formulation,

$$C_b(s) = K_c\left(1+\frac{1}{T_i s}\right). \tag{2}$$

A3. The feedforward controller $C_f(s)$ takes a PD formulation,

$$C_f(s) = K_f + \frac{T_a s}{T_f s+1}. \tag{3}$$

The first problem to be studied in this paper is to provide a design method for controllers $C_b(s)$ and $C_f(s)$ in Fig. 1. The second problem is on the performance assessment of the feedforward controller.

3. CONTROLLER DESIGN

This section provides a method to design the feedback and feedforward controllers to break the two fundamental tradeoffs: between the setpoint tracking and the load disturbance rejection, as well as between the setpoint tracking and the robustness against model uncertainties.

First, the feedback controller $C_b(s)$ is designed to reject the load disturbance $d(t)$, subject to an acceptable robustness of the control loop. For this purpose, the Direct-synthesis-disturbance (Ds-d) method proposed by Chen & Seborg (2002) is used. Given the process model $P(s)$ in (1), the Ds-d method gives the parameters of $C_b(s)$ in (2),

$$K_c = \frac{\tau\theta+2\tau\lambda-\lambda^2}{K(\lambda+\theta)^2},\ T_i = \frac{\tau\theta+2\tau\lambda-\lambda^2}{\tau+\theta}, \tag{4}$$

where λ is a user-selected parameter. With K_c and T_i in (4), the transfer function $G_{cd}(s)$ from $d(t)$ to $y(t)$ is

$$G_{cd}(s) = \frac{D(s)}{Y(s)} \approx \frac{Ks(\lambda+\theta)^2 e^{-\theta s}}{(\tau+\theta)(\lambda s+1)^2}. \tag{5}$$

Thus, the parameter λ stands for the desired time constant of $G_{cd}(s)$, which can be determined by achieving a balance between the speed of load disturbance response and robustness; see Yu *et al.* (2012) for a detailed procedure.

Second, the feedforward controller $C_f(s)$ is designed to provide a user-desired setpoint tracking response, typically in the formulation as an FOPDT model (Lee, 1998; Swanda, 1999; Skogestad, 2002; Panda, 2008),

$$G_c(s) = \frac{Y(s)}{R(s)} = \frac{P(s)\left(C_b(s)+C_f(s)\right)}{1+P(s)C_b(s)} = \frac{1}{\tau_c s+1}e^{-\theta s}. \tag{6}$$

Here τ_c is a user-selected parameter, standing for the desired closed-loop time constant. If τ_c is available, then it can be selected as presented later in Section 4. Given $P(s)$ in (1) and $C_b(s)$ in (2), in order to reach the desired closed-loop transfer function $G_c(s)$ in (6), the feedforward controller $C_f(s)$ is

$$\begin{aligned} C_f(s) &= \frac{\left(P(s)C_b(s)+1\right)G_c(s) - P(s)C_b(s)}{P(s)} \\ &= \frac{\left[\frac{K}{\tau s+1}e^{-\theta s}K_c\frac{T_i s+1}{T_i s}+1\right]\frac{e^{-\theta s}}{\tau_c s+1} - \frac{Ke^{-\theta s}}{\tau s+1}K_c\frac{T_i s+1}{T_i s}}{\frac{K}{\tau s+1}e^{-\theta s}} \\ &\approx \frac{[T_i\tau - KK_cT_i(\theta+\tau_c)]s + T_i - K_cK(\theta+\tau_c)}{KT_i(\tau_c s+1)} \end{aligned} \tag{7}$$

Here the first-order Taylor approximation is used for the term $e^{-\theta s} \approx 1-\theta s$ (see e.g., Skogestad, 2002) to reach the last equality. It is ready to obtain the PD form in (3) from $C_f(s)$ in (7), with the controller parameters

$$\begin{aligned} K_f &= \frac{T_i - K_cK(\theta+\tau_c)}{T_iK} \\ T_a &= \frac{\tau-\tau_c}{K} + \frac{K_c(\theta+\tau_c)(\tau_c-T_i)}{T_i} \\ T_f &= \tau_c. \end{aligned} \tag{8}$$

That is, by taking the parameters in (8), the feedforward PD controller $C_f(s)$ makes the closed-loop set-point response the same as the desired one in (6).

4. PERFORMANCE ASSESSMENT

This section first establishes the lower bound of TV for the SPFF control loop subject to ramp set-point changes. Taking the lower bound of TV and that of IAE established in our earlier work (Yu *et al.*, 2011) as benchmarks, an IAE-TV based performance index is proposed. Without loss of generality, the setpoint $r(t)$ is assumed to take a ramp form,

$$r(t) = \begin{cases} kt, & 0 \leqslant t < \dfrac{A}{k}, \\ A, & \dfrac{A}{k} \leqslant t < \infty. \end{cases} \tag{9}$$

4.1 IAE-TV-based performance index

The IAE and TV are used to measure the setpoint tracking performance and the control effort respectively (e.g., see Skogestad, 2002),

$$IAE := \int_0^\infty |r(t) - y(t)|\, dt \tag{10}$$

and

$$TV := \int_0^\infty \left| \frac{d\,(u(t))}{dt} \right| dt. \tag{11}$$

The objective is to obtain the lower bounds of IAE and TV for the SPFF control loop, and to devise a performance index by taking the lower bounds as benchmarks.

First, since the transfer function $G_c(s)$ from $r(t)$ to $y(t)$ is designed to be the FOPDT model in (6), the lower bound of IAE for the ramp setpoint $r(t)$ in (9), denoted as IAE_0, is (see Yu *et al.* (2011), eq. (12) therein)

$$IAE_0 = |A|(\tau_c + \theta). \tag{12}$$

Second, the lower bound of TV is derived as follows. The Laplace transform of $r(t)$ in (9) is

$$R(s) = \left(1 - e^{-\frac{A}{k}s}\right) \frac{k}{s^2}. \tag{13}$$

Using $P(s)$ in (1), $G_c(s)$ in (6) and $R(s)$ in (13), the Laplace transform of the control signal $u(t)$ is

$$\begin{aligned} U(s) &= \frac{G_c(s)R(s)}{P(s)} \\ &\approx \frac{\frac{1}{\tau_c s+1} e^{-\theta s} \left(1 - e^{-\frac{A}{k}s}\right) \frac{k}{s^2}}{\frac{K}{\tau s+1} e^{-\theta s}} \\ &= \frac{k}{K} \left(1 - e^{-\frac{A}{k}s}\right) \left(\frac{1}{s^2} + \frac{\tau - \tau_c}{s} + \frac{\tau_c^2 - \tau\tau_c}{\tau_c s + 1}\right) \end{aligned} \tag{14}$$

The inverse Laplace transform of $U(s)$ in (14) is

$$u(t) = \begin{cases} \dfrac{k}{K} \left[t + (\tau - \tau_c)\left(1 - e^{-\frac{t}{\tau_c}}\right)\right], & 0 \leqslant t < \dfrac{A}{k}, \\ \dfrac{k}{K} \left[\dfrac{A}{k} + (\tau - \tau_c)\left(e^{\frac{A}{k\tau_c}} - 1\right) e^{-\frac{t}{\tau_c}}\right], & \dfrac{A}{k} \leqslant t < \infty. \end{cases}$$

The derivative of $u(t)$ is

$$\begin{aligned} &\frac{d\,(u(t))}{dt} \\ &= \begin{cases} \dfrac{k}{K} \left(1 + \dfrac{\tau - \tau_c}{\tau_c} e^{-\frac{t}{\tau_c}}\right), & 0 \leqslant t < \dfrac{A}{k}, \\ \dfrac{k}{K} \dfrac{\tau - \tau_c}{\tau_c} \left(e^{\frac{A}{k\tau_c}} - 1\right) e^{-\frac{t}{\tau_c}}, & \dfrac{A}{k} \leqslant t < \infty. \end{cases} \end{aligned} \tag{15}$$

If $\tau_c \leqslant \tau$, substituting (15) into (11) yields the lower bound of TV,

$$TV_{0,\tau_c \leqslant \tau} = \left|\frac{k}{K}\right| \left[\frac{A}{k} + 2(\tau - \tau_c)\left(1 - e^{-\frac{A}{k\tau_c}}\right)\right]. \tag{16}$$

If $\tau_c > \tau$, the lower bound of TV is

$$TV_{0,\tau_c > \tau} = \left|\frac{A}{K}\right|.$$

Therefore, for a ramp setpoint $r(t)$ in (9), the lower bound of TV is

$$TV_0 = \begin{cases} \left|\dfrac{k}{K}\right| \left[\dfrac{A}{k} + 2(\tau - \tau_c)\left(1 - e^{-\frac{A}{k\tau_c}}\right)\right], & 0 < \tau_c \leqslant \tau, \\ \left|\dfrac{A}{K}\right|, & \tau < \tau_c < \infty. \end{cases} \tag{17}$$

If $r(t)$ is a step signal, it can be regarded as the special case of $r(t)$ in (9) for $k \to \infty$. For such a step setpoint, the lower bound of TV is obtained by applying the concept of equivalent infinitesimal $\left(1 - e^{-\frac{A}{k\tau_c}}\right) \approx \frac{A}{k\tau_c}$ to (17), i.e.,

$$TV_{0,step} = \begin{cases} \left|\dfrac{A}{K}\right| \dfrac{2\tau - \tau_c}{\tau_c}, & 0 < \tau_c \leqslant \tau, \\ \left|\dfrac{A}{K}\right|, & \tau < \tau_c < \infty. \end{cases} \tag{18}$$

Finally, taking the lower bound IAE_0 in (12) and the lower bound TV_0 in (17) as benchmarks, two dimensionless performance indices are respectively defined as

$$\eta_{IAE} = \frac{\min\left(IAE_0, IAE_{actual}\right)}{\max\left(IAE_0, IAE_{actual}\right)}, \tag{19}$$

and

$$\eta_{TV} = \frac{\min\left(TV_0, TV_{actual}\right)}{\max\left(TV_0, TV_{actual}\right)}. \tag{20}$$

Here IAE_{actual} and TV_{actual} stand for the actual IAE and TV, respectively.

Both indices η_{IAE} in (19) and η_{TV} in (20) are in the range of $[0, 1]$. By combining η_{IAE} and η_{TV}, an overall performance index is devised as

$$\eta = \eta_{IAE} \cdot \eta_{TV}. \tag{21}$$

Henceforth, η is referred to as the IAE-TV-based performance index, and provides a quantitative measurement of the setpoint tracking performance. The index η is in the range of $[0, 1]$ with the ideal value equal to 1. That is, $\eta \to 1$ indicates that the setpoint tracking performance of the current control loop is satisfactory, and in particular, both IAE_{actual} and TV_{actual} are close to the performance benchmarks IAE_0 in (12) and TV_0 in (17), respectively.

Remark #1 The proposed performance index η in (21) is equally applicable to other control schemes such as the setpoint weighted control loop (e.g., Alfaro, 2009) and the feedback plus setpoint feedforward and filter control loop (Aström and Hägglund, 2005), as long as the closed-loop response to setpoint change is the same as $G_c(s)$ in (6), and the process is an FOPDT model like $P(s)$ in (1). This is owing to a fact that the performance benchmarks IAE_0 in (12) and TV_0 in (17) are solely based on $G_c(s)$ and $P(s)$, and are irrelevant to the control scheme adopted.

Remark #2 A practical issue is on the effect of the measurement noise in $y(t)$ on the calculation of IAE_{actual} and TV_{actual}. The integral action (see the definition of IAE in (10)) makes IAE_{actual} robust to noise. However, the derivative action (see the definition of TV in (11)) implies that TV_{actual} is greatly influenced by the noise component in $u(t)$. To resolve this issue, the noise-free control signal $\hat{u}(t)$ is used instead of the actual measurement $u(t)$, and then $\hat{TV}_{actual}$ based on $\hat{u}(t)$ is actually used for the calculation of η_{IAE} in (19) and η_{TV} in (20). Note that $\hat{u}(t)$ is obtained as

$$\hat{U}(s) = \frac{(C_f(s) + C_b(s))\,\hat{P}(s)}{1 + C_b(s)} R(s), \tag{22}$$

where $\hat{P}(s)$ is the estimated of process model $P(s)$ in (1).

4.2 Selection of τ_c

The appearance of τ_c makes IAE_0 in (12) and TV_0 in (17) to be user-specified performance benchmarks. It is recommended to choose τ_c by achieving a balance between IAE and TV as follows.

First, $IAE_0(\tau_c)$ in (12) is a monotonic increasing function of τ_c. If $\tau_c \geqslant \tau$, the lower bound $TV_0(\tau_c)$ in (17) is a constant $\frac{A}{K}$, saying that the upper bound of τ_c is τ, in order to minimize $IAE_0(\tau_c)$ in (12).

Second, if $0 < \tau_c < \tau$, there is a *tradeoff* between $IAE_0(\tau_c)$ and $TV_0(\tau_c)$, namely, a smaller $IAE_0(\tau_c)$ is associated with a larger $TV_0(\tau_c)$. In this case, an optimal choice of τ_c can be obtained based on this tradeoff. Denote IAE_{min} and TV_{min} as the minimum values of $IAE_0(\tau_c)$ and $TV_0(\tau_c)$ as functions of τ_c, i.e.,

$$IAE_{min} = \min_{\tau_c}\{IAE_0(\tau_c)\} = IAE_0(\tau_c)|_{\tau_c=0_+} = |A|\theta,$$

$$TV_{min} = \min_{\tau_c}\{TV_0(\tau_c)\} = TV_0(\tau_c)|_{\tau_c=\tau} = \left|\frac{A}{K}\right|.$$

Using IAE_{min} and TV_{min} as normalization factors, two dimensionless metrics are introduced,

$$J_{IAE} = \frac{IAE_0(\tau_c)}{IAE_{min}} = \frac{\tau_c + \theta}{\theta}, \tag{23}$$

$$J_{TV} = \frac{TV_0(\tau_c)}{TV_{min}} = \frac{k}{A}\left[\frac{A}{k} + 2(\tau - \tau_c)(1 - e^{-\frac{A}{k\tau_c}})\right]. \tag{24}$$

Define a cost function as

$$J = \rho J_{IAE} + (1-\rho) J_{TV}, \tag{25}$$

where $\rho \in (0,1)$ is a real-valued weighting factor. The closer ρ is to 1, the more (less) important IAE (TV) will be. With J_{IAE} in (23) and J_{TV} in (24), the cost function J in (25) becomes

$$J = \rho\frac{\tau_c + \theta}{\theta} + (1-\rho)\frac{k}{A}\left[\frac{A}{k} + 2(\tau - \tau_c)(1 - e^{-\frac{A}{k\tau_c}})\right]. \tag{26}$$

Obviously, the value of τ_c minimizing J in (26) is related to k and A, saying that the optimal choice of τ_c for a ramp setpoint change depends on the slope and amplitude of the ramp change. To remove the dependence, it is suggested that the selection of τ_c is based on the control loop response subject to the step setpoint change instead of the ramp change. As $k \to \infty$, the cost function for a step setpoint change is

$$J_{step} = \rho\frac{\tau_c + \theta}{\theta} + (1-\rho)\frac{2\tau - \tau_c}{\tau_c}. \tag{27}$$

Differentiating J_{step} in (27) with respect to τ_c gives

$$\frac{\partial J_{step}}{\partial \tau_c} = \frac{\rho}{\theta} + (1-\rho)\frac{-2\tau}{\tau_c^2}.$$

Letting $\frac{\partial J_{step}}{\partial \tau_c} = 0$ provides the value of τ_c minimizing the cost function J_{step} in (27),

$$\tau_c = \sqrt{\frac{2\tau\theta(1-\rho)}{\rho}}.$$

Finally, to incorporate the above two cases, the recommended value of the desired time constant is

$$\tau_c = \min\left(\sqrt{\frac{2\tau\theta(1-\rho)}{\rho}}, \tau\right). \tag{28}$$

5. SIMULATION EXAMPLES

Example 1. In this example the process, defined as in Fig. 1, is considered as follows,

$$P(s) = \frac{1}{20s+1}e^{-s}. \tag{29}$$

The setpoint $r(t)$ experiences a ramp change shown as dashed line in Figure 2-(a). A unit step input load disturbance $d(t)$ is added into the control loop at time30 sec.

First, the feedforward controller is absent in the control loop. The feedback controller $C_b(s)$ in (2) follows the Ds-d method to reject the load disturbance. The desired time constant of the response $G_{cd}(s)$ in (5) from $d(t)$ to $y(t)$ is chosen as $\lambda = 3$, so that the controller parameters in (4) give

$$C_b(s) = 8.1875\left(1 + \frac{1}{6.2381s}\right). \tag{30}$$

The process output $y(t)$ and control signal $u(t)$ are shown as the dash-dotted lines in Fig. 2-(a) and (b), respectively. It is observed that the load disturbance rejection performance is acceptable; however, the setpoint tracking performance is aggressive with excessive overshoot.

Second, a setpoint feedforward controller $C_f(s)$ as that in Fig. 1 is introduced, with the same feedback controller $C_b(s)$ in (30). The desired time constant τ_c of the response $G_c(s)$ in (6) from $r(t)$ to $y(t)$ is selected as $\tau_c = 1.5$. The proposed controller design method in (8) yields the parameters of $C_f(s)$ as $K_f = -2.2813$, $T_a = 2.9531$, $T_f = 1.5$. The corresponding $y(t)$ and $u(t)$ are shown as the solid lines in Fig. 2-(a) and (b), respectively. As expected, the load disturbance rejection performance is the same as the case that $C_b(s)$ is used only, while the setpoint tracking performance has been much improved.

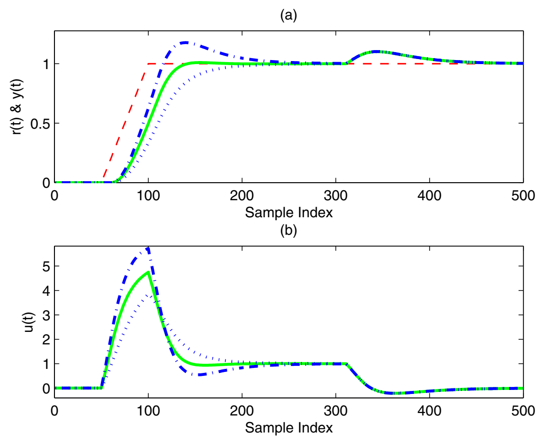

Fig. 2. Signals in Example 1

Third, the set-point weighted control scheme by Alfaro and Vilanova (2012b) is applicable here. To have the same load disturbance response, the feedback controller of the set-point weighted control scheme is the same as $C_b(s)$ in (30).

As suggested by Alfaro and Vilanova (2012b), the setpoint weighted factor is selected as 0.4809. The corresponding $y(t)$ and $u(t)$ are shown as the dotted lines in Figure 2-(a) and (b), respectively. The overshoot in the setpoint response by solely using the feedback controller is removed by the setpoint weighted PI controller $C_r(s)$; however, the setpoint response is confined by the selection of λ and is more sluggish than the response by using the proposed SPFF control scheme.

Example 2. The second example is to validate the lower bound TV_0 in (17). The configuration here is the same as that in Example 1. The feedback PI controller $C_b(s)$ takes the parameters $K_c = 1$ and $T_i = 20$. The weighting factor ρ gradually increases from 0.1 to 0.9; as a result, (28) yields different values of the closed-loop time constant τ_c. For each pair of ρ and τ_c, Table 1 reveals that the corresponding TV_{actual} is quite close to the theoretical lower bound TV_0 from (17). The minor difference between them is due to the approximation in (14).

Table 1. The actual TV and TV_0 for different pairs of ρ and τ_c

ρ	τ_c	K_f	T_a	T_f	TV_{actual}	TV_0
0.1	18.974	0.001	0.001	18.974	1.093	1.095
0.3	9.661	0.467	4.828	9.661	2.664	2.670
0.5	6.325	0.634	8.667	6.325	3.989	3.993
0.7	4.140	0.743	11.783	4.140	5.479	5.448
0.9	2.108	0.845	15.111	2.108	7.623	7.489

6. EXPERIMENTAL EXAMPLES

In this section, experiments are carried out at a laboratory at the Peking University to illustrate the steps of performance assessment for setpoint feedforward controllers.

The experiment setup the same configuration as that in Fig. 1. The process is a water tank system. The water level of the tank is selected as the process output $y(t)$. The discrete-time counterparts of the feedback controller $C_b(s)$ and feedforward controller $C_f(s)$ are implemented with the sampling period 0.5 sec in a DCS platform of Siemens PCS7. In the experiments, the feedback PI controller $C_b(s)$ in (2) is fixed to take the parameters $K_c = 1$ and $T_i = 20$. The control signal $u(t)$ is sent to a control valve to change the inlet flow rate.

In the first experiment, the feedforward controller $C_f(s)$ in (3) takes the parameters $K_f = 0.2$, $T_a = 3$ and $T_f = 15$. The measured process output $y(t)$ and control signal $u(t)$ are shown in thick-solid lines in Fig. 3 (a) and (b), respectively. Based on this closed-loop ramp response, a semi-nonparametric modeling method proposed by Veronesi & Visioli (2009) is implemented to yield the process is

$$\hat{P}(s) = \frac{6.6249}{172.1121 + 1} e^{-1.7385s}. \quad (31)$$

The weighting factor ρ is selected as $\rho = 0.8$ so that $\tau_c = 12.2315$ is obtained from (28). Next, the performance assessment results are listed in the second column of Table 2. In particular, the performance index $\hat{\eta} = 0.3437$ indicates that the performance of current feedforward controller is far from being satisfactory. Note that $\hat{\eta}_{TV}$ is calculated based on the estimated control signal $\hat{u}(t)$ from

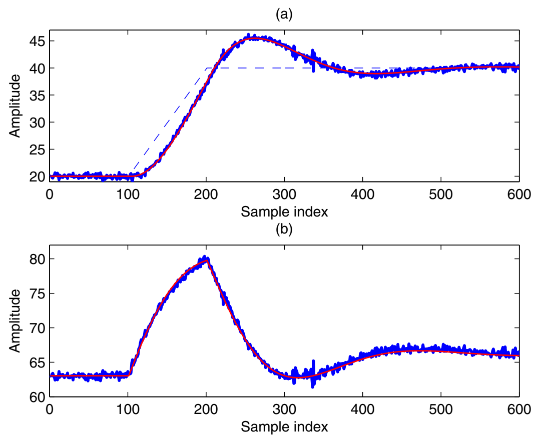

Fig. 3. Signals in the first experiment

(22). Finally, based on $\hat{P}(s)$ in (31) and $\tau_c = 12.2315$, (8) suggests that the parameters of $C_f(s)$ should be re-tuned as

$$K_f = -0.5476,\ T_a = 18.7070,\ T_f = 12.2315. \quad (32)$$

In the second experiment, the re-tuned parameters in (32) are applied into the feedforward controller $C_f(s)$. The measured process output $y(t)$ and control signal $u(t)$ are shown as the thick-solid lines in Fig. 4-(a) and (b), respectively. The corresponding performance assessment results are listed in the third column of Table 2. The performance index $\hat{\eta} = 0.9327$ indicates that a satisfactory setpoint tracking response is achieved.

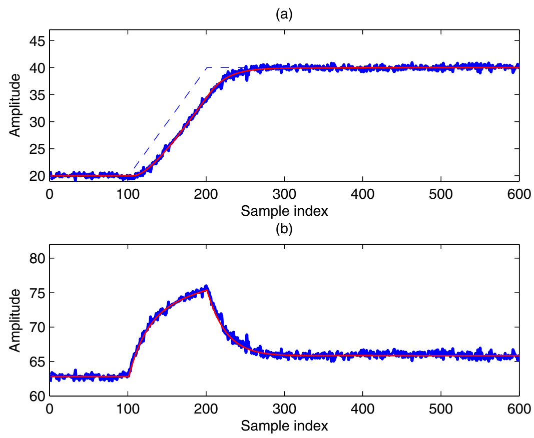

Fig. 4. Signals in the second experiment

Table 2. Comparison of performance assessment results for two experimental examples

K_f	0.2	-0.5476
T_a	3	18.7070
T_f	15	12.2315
IAE_{actual}	475.5890	298.2691
IAE_0 in (12)	279.3995	279.3995
η_{IAE} in (19)	0.5875	0.9367
$\hat{TV}_{actual}$	37.6034	22.0974
TV_0 in (16)	22.0016	22.0016
η_{TV} in (20)	0.5851	0.9957
η in (21)	0.3437	0.9327

7. CONCLUSION

This paper studied the design and performance assessment of setpoint feedforward controllers for univariate control loops. First, the setpoint feedforward controller $C_f(s)$ in (3) was introduced to break the two tradeoffs. Second, the lower bound of TV was established in (17) for the closed-loop response to a ramp setpoint change. An IAE-TV-based index η in (21) was proposed to assess the performance of the setpoint feedforward controller. The effectiveness of the proposed controller design method and the performance assessment method for the feedforward controller were illustrated via simulation and experimental examples.

REFERENCES

[1] Aström, K.J. & Hägglund, T. Revisiting the Ziegler-Nichols step response method for PID control, *J. Process Control*, 14, 635-650, 2004.

[2] Araki, M. & Taguchi, H. Two-degree-of-freedom PID Controllers, *Int. J. Control, Automation, and Systems*, 4(1), 401-411, 2003.

[3] Visioli, A. *Practical PID Control*, Springer, 2006a.

[4] S. Piccagli, & Visioli, A. *A feedward plus decoupling control design for set-point following of TITO processes*, American Control Conference (ACC2012), Montreal, Canada, June27-29, 2012, pp.2374-2379.

[5] Arrieta, O. & Vilanova, R. Simple servo/regulation proportional-integral-derivative (PID) tuning rules for arbitrary Ms-based robustness achievement, *Ind. Eng. Chem. Res.*, 51, 2666-2674, 2012.

[6] Hägglund, T. & Aström, K.J. Revisiting the Ziegler-Nichols tuning rules for PI control, *Asian J. Control*, 4(4), 364-380, 2002.

[7] Alfaro, V.M. & Vilanova, R. Robust tuning and performance analysis of 2DoF PI controllers for integrating controlled processes, *Ind. Eng. Chem. Res.*, 51, 13182-13194, 2012.

[8] Panagopoulos, H., Aström, K.J. & Hägglund, T. Design of PID controllers based on constrained optimisation, *IEE Control Theory Appl.*, 149, 32-40, 2002.

[9] Vijayan, V. & Panda, R.C. Design of a simple setpoint filter for minimizing overshoot for low order processes, *ISA Trans.*, 51, 271-276, 2012.

[10] Alfaro, V.M., Vilanova, R. & Arrieta, O. Considerations on set-point weight choice for 2-DoF PID controllers, *7th IFAC Int. Symp. Advanced Control of Chemical Processes*, Istanbul, Turkey, 721-726, 2009.

[11] Aström, K.J. & Hägglund, T. *Advanced PID Control*, ISA-The Instrumentation, Systems, and Automation Society, 2005.

[12] Jelali, M. An overview of control performance assessment technology and industrial applications, *Control Eng. Pract.*, 14, 441-466, 2006.

[13] Harris, T.J. Assessment of closed loop performance, *Can. J. Chem. Eng.*, 67, 856-861, 1989.

[14] Huang, B. & Shah, S.L. *Performance Assessment of Control Loops: Theory and Applications*, Springer-Verlag, 1999.

[15] Ko, B.S. & Edgar, T.F. Assessment of achievable PI control performance for linear processes with dead time, *Proc. American Control Conf.*, PA, 1548-1552, 1998.

[16] Ko, B.S. & Edgar, T.F. PID control performance assessment: The single-loop case, *AIChE J.*, 50(6), 1211-1218, 2004.

[17] Jain, M. & Lakshminarayanan, S. A filter-based approach for performance assessment and enhancement of SISO control systems, *Ind. Eng. Chem. Res.*, 44, 8260-8276, 2005.

[18] Hägglund, T. Automatic detection of sluggish controlloops, *Control Eng. Pract.*, 7, 1505-1511, 1999.

[19] Visioli, A. Method for proportional-integral controller tuning assessment, *Ind. Eng. Chem. Res.*, 45, 2741-2747, 2006b.

[20] Veronesi, M. & Visioli, A. Performance assessment and retuning of PID controllers, *Ind. Eng. Chem. Res.*, 48, 2616-2623, 2009.

[21] Yu, Z., Wang, J., Huang, B. & Bi, Z. Performance assessment and retuning of PID controllers subject to setpoint changes, *J. Process Control*, 21, 1164-1171, 2011.

[22] Yu, Z. & Wang, J. Assessment of PI control-loop performance for input load disturbance rejection, *Ind. Eng. Chem. Res.*, 51(36), 11744-11752, 2012.

[23] Srinivasan, B., Spinner, T. & Rengaswamy, R. Control loop performance assessment using detrended fluctuation analysis (DFA), *Automatica*, 48(7), 1359-1363, 2012.

[24] Petersson, M., Arzén, K.E. & Hägglund, T. A comparison of two feedforward control structure assessment methods, *Int. J. Adapt. Control Signal Process.*, 17, 609-624, 2003.

[25] Olaleye, F.B., Huang, B. & Tamayo, E. Feedforward and feedback controller performance assessment of linear time-variant processes, *Ind. Eng. Chem. Res.*, 43, 589-596, 2004.

[26] Ko, B.S. & Edgar, T.F. Performance assessment of cascade control-loops, *AIChE J.*, 46, 281-291, 2000.

[27] Veronesi, M. & Visioli, A. Simultaneous closed-loop automatic tuning method for cascade controllers, *IET Control Theory Appl.*, 5, 263-270, 2011.

[28] Seborg, D., Edgar, T.F. & Mellichamp, D.A. *Process Dynamics and Control*, 2nd Ed., John Wiley & Sons, 2004.

[29] Chen, D. & Seborg, E. PI/PID controller design based on direct synthesis and disturbance rejection, *Ind. Eng. Chem. Res.*, 41, 4807-4822, 2002.

[30] Lee, Y., Lee, M., Park, S. & Brosilow, C. PID controller tuning for desired closed-loop responses for SI/SO systems, *AIChE J.*, 44(1), 106-115, 1998.

[31] Swanda, A.P. & Seborg, D.E. Controller performance assessment based on set-point data, *American Control Conf.*, 6, 3863-3867, 1999.

[32] Skogestad, S. Simple analytic rules for model reduction and PID controller tuning, *J. Process Control*, 13, 291-309, 2002.

[33] Panda, R.C. Synthesis of PID tuning rule using the desired closed-loop response, *Ind. Eng. Chem. Res.*, 47, 8684-8692, 2008.