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Design of a simple setpoint filter for minimizing overshoot for low order processes

V. Vijayan [a], Rames C. Panda [b,*]

[a] Department of E&I, St. Joseph's College of Engineering, IT Highway, Chennai – 600119, India

[b] Department of Chemical Engineering, CLRI (CSIR), Adyar, Chennai – 600 020, India

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ABSTRACT

Setpoint filters are widely used along with a PID controller. The aim of the present paper is to reduce the peak overshoot to a desired/tolerable limit. To design a setpoint filter, numerous methods are available, which need extensive calculations. Moreover, the existing methods need information regarding the process parameters, values of controller settings and are laborious. But the proposed method is very simple and requires only the information about the peak overshoot and peak time of the system response regardless of type and order of the system with arbitrary PID parameters. Several examples are taken to show efficacy of the process.

1. Introduction

Most of the industrial loops use PID controllers till today. These types of controllers are popular because of their ease in operation, robust behavior, and easy maintenance. Even after the invention of advanced process control strategies, predictive controllers etc., use of a PID controller dominates process industries. Generally, PID controllers have four different structures [1] out of which three are implementable. The accuracy and performance of these controllers are greatly dependent on the method of tuning controller parameters, namely, K_C, τ_I, and τ_D. Researchers have proposed a number of tuning rules to improve loop performance.

There are many industrial processes, which need to be operated at unstable operating points for economic and safety reasons. Researchers [2] proposed setpoint weighted PID controllers to control these systems. Presence of large dead time in unstable processes makes the system more difficult to control. Different structures (conventional feedback, modified smith predictor, modified IMC, two-degrees of freedom etc.) have been proposed to improve the closedloop performance. But, in all the above works, either the closed-loop structure or the tuning designed for specific systems has improved closed-loop performances (evaluated by error criteria). The literature does not show much evidence to reduce overshoot in closed-loop responses of these methods. Shamsuzzoha and Lee [3] designed setpoint filters to improve loop performances using an IMC Maclaurian PID controller. Recently, Shamsuzzoha and Skogestad [4] derived PID tuning rules based on closedloop tests that reduced overshoot of the system. Most of the unstable systems and processes with numerator zero yield overshoot in their closed loop responses mainly due to improper tuning. Hence, in order to improve the time domain performances, new design procedures are proposed here to achieve the desired overshoot using simple calculations. Several examples from IPDT, FOPDT, SOPDT, HOPDT and multivariable systems are chosen to implement the present method and results are achieved in this study. Thus the entire paper is organized as follows. Section 2 discusses a design technique of the proposed setpoint filter. Examples of processes with different model structure are taken and setpoint filters are designed in Section 3. Real time experimental results are presented in Section 4. Conclusion is drawn in Section 5.

2. Set point filter design

Fig. 1 shows the actual closed-loop response of a typical process (Gp) with a PID controller. The response oscillates around the set point with first peak overshoot at Mp1 at a corresponding time tp1. Let us think that the response can be approximated by a FOPDT transfer function that will yield a desired closed loop response with the desired overshoot. The design is based on the idea that: if a first order system is assumed, the closed loop

* Corresponding author. Fax: +91 44 24911589.
E-mail address: panda@clri.res.in (R.C. Panda).

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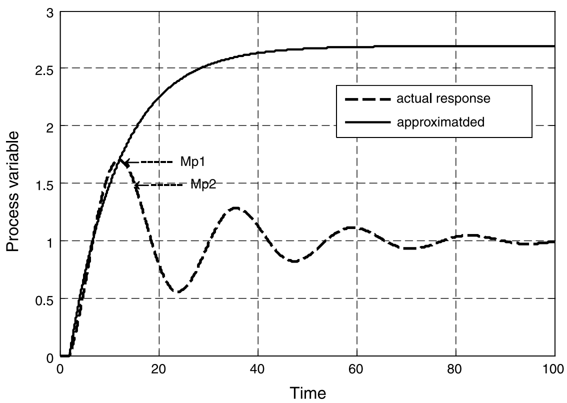

Fig. 1. Peak over shoot response of existing process and approximation curve.

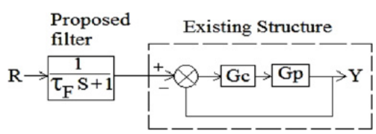

Fig. 2. The existing structure with PID settings. (The proposed filter is used along with existing structure.)

response will pass through the peak overshoot (Mp1) only when the peak time is equal to time constant (τ) of the first order system. Let the desired overshoot of the closed loop response be Mp2 and the corresponding peak time be tp2. Let us also design a FOPDT system with gain $k = \text{Mp1}/0.6321$ so that the time constant of the designed system can be written as $\tau = \text{tp1}$. Thus the transfer function of the approximated system becomes $\frac{y(s)}{u(s)} = \frac{ke^{-Ds}}{\tau s+1}$ and actual process becomes $G_P = \frac{B(s)e^{-Ds}}{A(s)}$ where B and A are polynomials of s. Now, after introducing a setpoint filter with the existing structure (Fig. 2), the system transfer function can be written as $\frac{y(s)}{u(s)} = \frac{ke^{-Ds}}{\tau s+1} * \frac{1}{\tau_f s+1}$. This setpoint filter will bring down the peak over shoot from Mp1 to Mp2. The inverse Laplace transform of the above TF for step input can be written as

$$y(t) = \left(\frac{k}{\tau - \tau_f}\right) * \left[\tau_f e^{-t'/\tau_f} - \tau e^{-t'/\tau}\right] + k. \quad (1)$$

From Fig. 1, it can be noted that, the desired over shoot is Mp2 and its corresponding peak time is tp2. So, at $t = \text{tp2} + D$, $y(t)$ is equal to Mp2. So Eq. (1) becomes,

$$\text{Mp2} = \left(\frac{k}{\tau - \tau_f}\right) * \left[\tau_f e^{-\text{tp2}/\tau_f} - \tau e^{-\text{tp2}/\tau}\right] + k. \quad (2)$$

It is well known that the filter time constant t_f is always less than process time constant. So $e^{-\text{tp2}/\tau_f}$ is very less than $e^{-\text{tp2}/\tau}$. So Eq. (2) can be written as

$$\text{Mp2} = \left(\frac{k}{\tau - \tau_f}\right) * \left[-\tau e^{-\text{tp2}/\tau}\right] + k. \quad (3)$$

From the above equation, τ_f can be calculated

$$\tau_f = \tau \left(\frac{k - \text{Mp2} - k * e^{-\text{tp2}/\tau}}{k - \text{Mp2}}\right). \quad (4)$$

The steps of the calculations under present procedure are as follows.

(a) Note down dead time and actual peak over shoot with out filter = Mp1 and the corresponding peak time = tp1 + D from the response.
(b) Assume that the approximated FOPDT process gain $k = \text{Mp1}/0.6321$.
(c) Assume that the time constant of the approximated FOPDT process $\tau = \text{tp1}$.
(d) Find the desired overshoot (Mp2) and time corresponding peak time (tp2 + D) from the response.
(e) Calculate filter time constant (τ_f) from Eq. (4).

3. Results and discussion

The examples considered for simulation are provided in Table 1.

Example 1 (*Stable First Order Plus Dead Time Process (FOPDT)*)**.** Consider the following stable FOPDT process [5].

Ex-1 and the controller settings used were $kc = 1.8$, $\tau_I = 1.655$ and set point weight $\beta = 0.63$. A setpoint filter is designed for the same process and controller settings to reduce the overshoot. The proposed filter transfer function is $G_F = \frac{1}{0.5839s+1}$. Results (Fig. 3) show almost similar values of overshoot (Table 1) with improved performance (ITAE with present technique, using setpoint filter, becomes 1.921 whereas with setpoint weight, Chidambaram [5] obtained ITAE of 2.479).

Example 2 (*Unstable FOPDT System*)**.** Let us take the following FOPDT process [6]: $G_p = \frac{e^{-0.5s}}{s-1}$ and the controller settings used were $kc = 1.5353$, $\tau_I = 7.5753$ with setpoint filter $G_F = \frac{1}{7.5753s+1}$. For the same process with same controller settings the designed/proposed filter transfer function became $G_F = \frac{1}{7.9248s+1}$. The closedloop simulation results (table) show lesser peak overshoot and with improved time domain performances proving the efficiency of present method. Moreover, the present procedure of filter design is very simple and straight forward.

Present results are almost in close agreement to Shamsuzzoha and Lee [3]. However, the method proposed by the latter is laborious compared to the present one.

Example 3 (*Stable Second Order Plus Dead Time Process (SOPDT)*)**.** Consider a stable SOPDT process [3] as Ex-3 (Table 1) with the PID controller parameters as $kc = 9.8092$, $\tau_I = 5.4502$, $\tau_D = 1.6898$. The peak overshoot (PO) reported was 1.009. Using the present method, a setpoint filter is designed with $\tau_f = 3.2612$. Closedloop simulation resulted in a PO of lesser value, 1.0002, and better performance values (Table 1) are obtained compared to Shamsuzzoha and Lee [3] who used a second order filter.

Example 4 (*Second Order Plus Dead Time Plus Unstable Process (SODUP—One Unstable Pole)*)**.** As an unstable SODUP process [3], let us take Ex-4 as mentioned in Table 2. The PID controller settings used are $kc = 6.7051$, $\tau_I = 5.4738$, $\tau_D = 1.333$ and a second order filter with transfer function $G_F = \frac{1.6421s+1}{7.2966s^2+5.4738s+1}$ was used that yielded a PO of 1.03 (Table 1). Whereas by using the present method, a first order filter was designed whose $\tau_f = 3.9636$. After the closed-loop simulation with same PID settings, better performance values are obtained with less PO value of 1.0055.

Example 5 (*SOPDT with Inverse Response*)**.** Next example is chosen as an SOPDT process with a zero in numerator that often shows inverse response as also was considered by Shamsuzzoha and Lee [3]. The PIOD parameter was set to be $kc = 3.0819$, $\tau_I = 1.6399$, $\tau_D = 0.4295$ for this Ex-5 and a second order filter with transfer function $G_F = \frac{1}{0.7044s^2+1.6399s+1}$ was used. They obtained a PO of 1.274 (printed value is 1.274 however, we calculated it as 1.000) and ITAE of 2.751. By using the present method, a setpoint filter with time constant $\tau_f = 0.9024$ is obtained and after simulation, an ITAE value of 1.188 is obtained. Thus the performance of the system is improved by the present setpoint filter. The closed loop response is shown in Fig. 3 and the performance values for this example are given in Table 1.