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A simple robust PI/PID controller design via numerical optimization approach

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Abstract

This paper presents a simple but effective method for designing robust PI or PID controller. The robust PI/PID controller design problem is solved by the maximization, on a finite interval, of the shortest distance from the Nyquist curve of the open loop transfer function to the critical point-1. Simulation studies are used to demonstrate the effectiveness of the proposed method.
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1. Introduction

The proportional-integral (PI) and proportional-integral-derivative (PID) controllers are widely used in many industrial control systems for several decades since Ziegler and Nichols proposed their first PID tuning method. This is because the PID controller structure is simple and its principle is easier to understand than most other advanced controllers. On the other hand, the general performance of PID controller is satisfactory in many applications. For these reasons, the majority of the controllers used in industry are of PI/PID type.

Most of real plant operate in a wide range of operating conditions, the robustness is then an important feature of the closed loop system. When this is the case, the controller has to be able to stabilize the system for all operating conditions. To this end, it is possible to employ an internal-model-based PID tuning method [12,4]. However, this method gives very slow response to load disturbance for lag-dominant processes because of the pole-zero cancellations inherent in the design methodology [2]. Another popular approach with similar emphasis is the tuning of PI or PID controller by the gain and phase margin specifications [9,1]. Gain margin and phase margin have always served as important measures of robustness. It is well known that phase margin is related to the damping of the system, and can therefore also serve as a performance measure [6]. In this way, numerous progress has been made to improve the performances of the PI/PID control [8]. In particular, tuning methods based on optimization approach have recently received more attention in the literature, with the aim of ensuring good stability robustness of the controlled system [10,7]. However, these new methods are not easy to use for the operating engineer who is the main user of the PI/PID controller.

The objective of this paper is to propose a novel robust PI or PID controller which is simple and easy to use.

The paper is organized as follows. Section 2 presents the process models used for the synthesis of the PI or PID controller. In Section 3, the robust PI/PID controller design problem is formulated and solved by the maximization, on a finite interval, of the shortest distance from the Nyquist curve of the open loop transfer function to the critical point-1. Simulation studies are conducted in Section 4 and comparison with the works of other authors are given. Section 5 concludes this paper.

2. Process models

The industrial processes are of an extreme variety. Nevertheless, a very broad class is characterized by

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aperiodic response. This important category of industrial systems can be represented by a first-order plus dead time model, as follows:

$$G(s) = \frac{k e^{-t_0 s}}{1 + \tau s} \tag{1}$$

Note that the above process model is only used for the purpose of simplified analysis. The actual process may have multiple lags, non-minimum phase zero, etc. Another important class of industrial processes is characterized by non-aperiodic response. This category of processes can be represented by a second-order plus dead-time model, as follows:

$$G(s) = \frac{k e^{-t_0 s}}{s^2 + a_1 s + a_0} \tag{2}$$

Many identification techniques can be used to obtain first-order plus dead-time or second-order plus dead-time model for PI/PID control [5,3]. A simple method is based on the analysis of the open-loop step response. The first-order plus dead-time model (1) is obtained as follows:

$$\begin{cases} k = y_\infty \\ t_0 = 2.8t_1 - 1.8t_2 \\ \tau = 5.5(t_2 - t_1) \end{cases} \tag{3}$$

where y_∞ is the final value of the step response of the process, t_1 (respectively, t_2) is the time where the output attains 28% (respectively 40%) of its final value. For the second-order plus dead-time model (2), the parameters are obtained as follows:

$$\begin{cases} k = y_\infty \\ t_0 : \text{ is the apparent time delay} \\ a_1 = \frac{2|\ln(D_1)|}{\pi t_p}, \quad a_0 = \frac{\pi^2 + \ln(D_1)^2}{\pi^2 t_p^2} \end{cases} \tag{4}$$

where D_1 is the first overshoot for the unit step response of the process and t_p is the corresponding time. Alternatively, these models can be derived from relay feedback method [2,1]. This method can be extended to open-loop unstable processes [13,11].

3. Robust PI/PID controller design

In this section, the robust PI/PID controller design problem is formulated and solved via numerical optimization method.

3.1. Problem statement

Consider the PID feedback control system shown in Fig. 1, in which $G(s)$ represents the transfer function of the process model (1) or (2) and $K(s)$ is the transfer function of the standard PI/PID controller

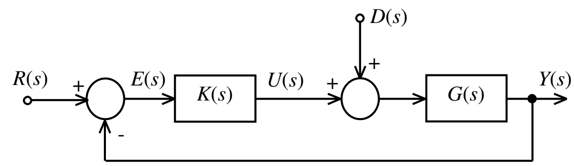

Fig. 1. Block diagram of the PID feedback control system.

$$\begin{cases} \text{PI}: & K(s) = k_p + \frac{k_i}{s} \\ \text{PID}: & K(s) = k_p + \frac{k_i}{s} + k_d s \end{cases} \tag{5}$$

For this control system, the sensitivity function $S(s)$ and complementary sensitivity function $T(s)$ which is the transfer function of the closed loop system, are respectively, defined by

$$S(s) = \frac{1}{1 + K(s)G(s)} = \frac{1}{1 + L(s)} \tag{6}$$

where $L(s) = K(s)G(s)$ is the open-loop transfer function, and

$$T(s) = 1 - S(s) = \frac{L(s)}{1 + L(s)} \tag{7}$$

The quantity $|T(j\omega)|$ represents the input-output gain at the frequency $2\pi/\omega$, for a PI/PID controller this gain is equal to one in the low frequency domain, that is the steady-state error is equal to zero. The quantity $M_p = \max_\omega |T(j\omega)|$ is the peak magnitude of the frequency response of the closed-loop system. It is well known that M_p is related to the overshoot for the step response of the closed-loop system. In order to impose good transient response it is necessary to have

$$M_p \leqslant M_p^+ \tag{8}$$

where $M_p^+ > 1$ is the upper bound of the maximum of the complementary sensitivity function. In an equivalent manner the following constraint is required:

$$D_1 \leqslant D_1^+ \tag{9}$$

where D_1 is the first overshoot of the step response and D_1^+ is the upper bound value of this overshoot. It is then possible to introduce a lower bound pseudo-damping factor ζ_m, which is related to the upper bound of the first overshoot by the relation:

$$\zeta_m = \frac{|\ln(D_1^+)|}{\sqrt{\pi^2 + \ln(D_1^+)^2}} \tag{10}$$

the relation between M_p^+ and the lower bound pseudo-damping factor ζ_m, is given by [14]

$$M_p^+ = \frac{1}{2\zeta_m\sqrt{1 - (\zeta_m)^2}} \tag{11}$$

For a good transient response it is then required that

$$\zeta \geqslant \zeta_m \tag{12}$$

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