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Nonlinear CSTR control system design using an artificial bee colony algorithm

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ABSTRACT

This paper proposes a novel controller design method based on using artificial bee colony (ABC) algorithms for an unstable nonlinear continuously stirred tank reactor (CSTR) chemical system. Such CSTR process is highly nonlinear and its dynamic is significantly dominated by system parameters. It is a good challenge to access the controller design performance when the controller is applied in the CSTR control system. The commonly used proportional–integral-derivative (PID) controller is taken into account in this study, and tuning three PID control gains is carried out by the artificial bee colony algorithm. With the use of the optimal ABC algorithm, PID controller gains can be derived suitably by means of minimizing the cost function given in advance. Finally, several control operations are provided to confirm the feasibility and effectiveness of the proposed method. We also discuss the influence of algorithm initial conditions on the control performance with many different tests.

1. Introduction

Continuously stirred tank reactor (CSTR) is an important and basic process system in chemical industries. It is a highly nonlinear system and has a rather complex dynamic behavior dominated by its system parameters heavily. To design a suitable controller for such CSTR systems, it is somewhat difficult and need more efforts [1–5]. Recently, some novel control strategies have been developed for the CSTR system, for example, Chen and Dai proposed a robust design methodology that combines differential geometric feedback linearization, sliding mode control, and adaptive state feedback to control the CSTR system in the presence of uncertainties, and a Lyapunov-based scheme is utilized to guarantee the stability of the closed-loop system [2]. In [3], they showed an intelligent process control technique to control complex, unknown, and uncertain nonlinear dynamic system, which is based on using fuzzy logic system and neural network. A neuro-fuzzy direct controller is designed to control an open-loop unstable CSTR process system. In addition, an adaptive tracking control was considered for a class of nonlinear systems based on neural networks [5]. The goal of applying neural networks is to realize the feedback linearization approximately. Then the adaptive controller is taken to control the composition of a CSTR.

For CSTP control system design, however, this study will focus on the proportional–integral-derivative (PID) controller structure. It is well known that PID controller is rather popular and often utilized in most chemical industry applications due to the advantages of simple architecture and easy implementation. In the structure of PID controller, there are three designed control gains including the proportional gain K_p, integral gain K_i, and derivative gain K_d. Traditionally, the famous design method for PID controller is the Ziegler–Nichols (ZN) tuning method. The process is first modeled by a first-order system plus a transportation delay, and then system constants are determined according to the step response of the process.

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Finally, based on this process model PID control gains are given according to a decay ration of 0.25 and the limit of stability, respectively [6]. In addition, a large number of new design methods have been developed for PID control systems in recent years, which are based on the swarm intelligence (SI) such as particle swarm optimization (PSO), differential evolution (DE), genetic algorithms (GAs), and other related evolving algorithms [7–11]. They search for the optimal (global) solution of the given problem in parallel throughout the search space using respective adjusting mechanisms. This is due to the contribution of population (swarm) concept of the algorithm. Generally, a population comprises a large number of possible candidate solutions called particles used in PSO, parameter vectors in DE, or chromosomes in GAs, respectively. Then the adjusting mechanisms are performed on these candidate solutions to generate a new offspring population with better performance than that of present generation. This procedure continues until the stopping criterion is met. In [8], a modified PSO algorithm was presented to solve the PID control design problem in the tracking control of nonlinear inverted pendulum systems. Simulation results show the applicability of the design scheme. Kim proposed a hybrid method which combines the conventional GA and bacterial foraging (BF) to search for the PID control parameters. The controlled plant is the automatic voltage regulator (AVR) system applied in the power application [9].

Artificial bee colony (ABC) algorithm is one of the newest optimal algorithms initially proposed by Karaboga in 2005 [12]. Like other swarm intelligence methods, it was also a population-based evolutionary computation and has been shown to be a powerful and efficient algorithm for solving the optimization problem. The concept of the ABC algorithm is intuitively motivated by the intelligent behavior of honey bee swarm. In [13], the authors showed that for optimizing multivariable functions the proposed ABC outperforms other algorithms such as GA, PSO, and particle swarm inspired evolutionary algorithm (PS-EA). On the basic of ABC algorithm, researchers have successively developed many applications including digital IIR filter design [14], cluster analysis [15], parametric optimization of non-traditional machining processes [16], etc. Moreover, a good survey on the ABC algorithm and its related applications has just been presented in [17]. Up to now, however, the research which applies the ABC algorithm to the optimal design of PID control tuning has rarely been reported. Consequently, based on using ABC algorithm this paper focuses on the PID control system design for a nonlinear CSTR system. We will perform four different control operations to verify the applicability of the proposed method. The remainder of this paper is organized in the following. In Section 2, the system description of a CSTR is presented in detail, and the PID controller structure is also simply described. In Section 3, we first introduce the basic concept and some central components of the ABC algorithm, and then based on this algorithm a complete design guideline of PID controller is presented for nonlinear CSTR system. Section 4 will show various control operations and some simulation comparisons with the real-coded genetic algorithm (RGA) are also given. Finally, a brief conclusion is addressed in Section 5.

2. System description of nonlinear chemical CSTR process

It is well known that most of nonlinear dynamic systems have rather complex behavior and are difficult to analyze or to control. A typical representative of nonlinear system in chemical processes is continuously stirred tank reactor (CSTR) system. This system exhibits some complex features such as its dynamics heavily depending on system parameters and having multiple equilibrium points (stable and unstable ones). To control such a CSTR process system, it has a considerable difficulty and needs more efforts than controlling general linear systems. The CSTR contains various mathematical models, for example, SHARON model (single reactor system for high activity ammonia removal over nitrite) [18], nonisothermal CSTR model [19], and CSTR model by considering thermodynamics based arguments [20], and so on. If certain operating conditions and parameter value settings are satisfied, these systems may have up to three equilibrium points. In this study, let us consider the following CSTR model expressed by [3,21]

$$\dot{x}_1 = -x_1 + D_a(1 - x_1)\exp\left(\frac{x_2}{1 + x_2/\varphi}\right), \tag{1a}$$

$$\dot{x}_2 = -(1+\delta)x_2 + B \cdot D_a(1 - x_2)\exp\left(\frac{x_2}{1 + x_2/\varphi}\right) + \delta \cdot u, \tag{1b}$$

$$y = x_1, \tag{1c}$$

where x_1 and x_2 denote the dimensionless reactant concentration and reactor temperature, respectively, the control input u is the dimensionless cooling jacket temperature, $y = x_1$ is the system output. System parameters consist of D_a, φ, B, and δ that correspond to the Damökhler number, activated energy, heat of reaction, and heat transfer coefficient, respectively, and their nominal values are given by $D_a = 0.072$, $\varphi = 20$, $B = 8$ and $\delta = 0.3$. The open-loop CSTR system; that is, setting $u = 0$, has three equilibrium points, $(x_1, x_2) = (0.144, 0.886)_s$, $(x_1, x_2) = (0.445, 2.74)_u$, and $(x_1, x_2) = (0.765, 4.705)_s$, respectively. It is noted that the first and third equilibrium points are stable and the middle is an unstable equilibrium point. We can clearly see the phase portrait of x_1 and x_2 from Fig. 1 for these three different equilibrium points. In the viewpoint of control, it is a good challenge to bring system states from the stable point to the unstable point. It is somewhat like the dynamics of the inverted pendulum system, controlling the stable equilibrium point $(0,0)$ to the unstable point $(\pi,0)$. It needs much more efforts.

The central purpose of this study is to propose an adequate design approach to control such a nonlinear CSTR system in which the proportional–integral-derivative (PID) controller is considered. Thus, in Eq. (1b) the input u is the PID control law. Within the PID controller, there are three control parameters to be determined, i.e., the proportional gain K_p, integral gain K_i,