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Optimum Design of Fractional Order PID Controller for an AVR System Using an Improved Artificial Bee Colony Algorithm

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Abstract Fractional order proportional-integral-derivative (FOPID) controller generalizes the standard PID controller. Compared to PID controller, FOPID controller has more parameters and the tuning of parameters is more complex. In this paper, an improved artificial bee colony algorithm, which combines cyclic exchange neighborhood with chaos (CNC-ABC), is proposed for the sake of tuning the parameters of FOPID controller. The characteristic of the proposed CNC-ABC exists in two folds: one is that it enlarges the search scope of the solution by utilizing cyclic exchange neighborhood techniques, speeds up the convergence of artificial bee colony algorithm (ABC). The other is that it has potential to get out of local optima by exploiting the ergodicity of chaos. The proposed CNC-ABC algorithm is used to optimize the parameters of the FOPID controller for an automatic voltage regulator (AVR) system. Numerical simulations show that the CNC-ABC FOPID controller has better performance than other FOPID and PID controllers.

Key words Fractional order proportional-integral-derivative (FOPID) controller, optimal control, artificial bee colony algorithm, cyclic exchange neighborhood, chaos, automatic voltage regualator (AVR) system

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Fractional calculus is a generalization of integer orders calculus and it extends regular integer orders to non-integer orders case. Compared to classical integer calculus, fractional calculus computationally requires large memory which makes it able to represent the dynamics of the real system more exactly. In the area of control theory and control engineering, the proportional-integral-derivative (PID) control is the most widely utilized control method because of its simple structure and strong robustness. Nowadays, more than 90 % controllers in industry are PID controllers[1].

In recent years, the combination of fractional calculus and PID control theory has got much attention of researchers. Fractional order PID (FOPID) controller was proposed by Podlubny in 1999[2], which is written as $PI^{\lambda}D^{\mu}$, where λ and μ are the integrating and derivative orders and they are non-integers. FOPID controller has five parameters, i.e., the proportional gain, the integral gain, the derivative gain, the integrating order, and the derivative order. Compared to PID controller, FOPID has extra two parameters, i.e., the integrating order λ and the derivative order μ, which means that researchers have more freedom in the designing of FOPID controller. On the other hand, its parameters tuning is more complex. Different methods for tuning the parameters of FOPID controllers have been reported in the literatures. Valério et al. proposed Ziegler-Nichols type tuning rules for FOPID controller[3]. Cervera et al. applied quantitative feedback theory (QFT) to tune the FOPID controller[4]. Genetic algorithm[5], differential evolution (DE)[6], particle swarm optimization (PSO)[7], and ant colony optimization (ACO)[8] were also used to design FOPID controller.

Artificial bee colony (ABC) algorithm was proposed by Karaboga in 2005[9]. It imitates the intelligent foraging behavior of honey bees to solve numerical optimization problems[9−13]. ABC algorithm has the characteristics of simplicity and ease of implementation. Many practical problems such as fractional order controller[14], clustering[15] and lot-streaming flow shop scheduling problem[16] have been solved using ABC algorithm. However, there are two disadvantages associated with ABC algorithm, i.e., the convergence speed is slow and it is often trapped into local optima. Many authors make efforts to overcome the drawbacks of ABC. Bao et al. proposed a chaos-artificial bee colony algorithm of self-adapting search space[17]. Lee et al. improved ABC algorithm based on diversity strategy[18]. Gao et al. improved ABC combined differential evolution algorithm[19].

In nature, ABC algorithm can be viewed as a class of neighborhood search algorithm (NSA). Many difficult optimization problems have been solved by using NSA. NSA obtains the optimal solution by searching the "neighborhood" of the current solution. Selecting an appropriate neighborhood structure is important for NSA because the neighborhood structure determines whether the solutions are highly accurate or very poor. Several powerful neighborhood structures have been presented such as compound neighborhood structures[20−21], multi-exchange neighborhood structure[22] etc. The multi-exchange neighborhood consists of two types of structure: cyclic exchange and path exchange. The advantage of multi-exchange neighborhood is that it can identify improvement moves in an associated improvement graph. In the literature, multi-exchange neighborhood structure algorithms have been applied to many complicated optimization problems. Tang et al.

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proposed an iterated local search (ILS) algorithm based on cyclic exchange neighborhood to solve parallel machine scheduling problems[23]. Ahuja et al. solved the capacitated minimum spanning tree problems by multi-exchange neighborhood[22]. Frangioni et al. applied multi-exchange neighborhood for minimum makespan parallel machine scheduling problems[24]. Thompson et al. presented a cyclic transfer neighborhood method for multi-vehicle routing and scheduling problems[25].

In this paper, a modified ABC algorithm is presented using cyclic exchange neighborhood and chaos for tuning the parameters of the FOPID controller. Exchanging neighborhood enables to enlarge the search scope of the solutions, so as to speed up the convergence of the algorithm. The ergodicity and randomness of the chaos make the algorithm be able to jump out of local optima.

This paper proceeds as follow. Section 1 briefly reviews the basic of fractional calculus. In Section 2, the behavior of honey bees foraging, ABC algorithm and the cyclic exchange neighborhood structure are firstly reviewed. Then, the modified ABC algorithm based on cyclic exchange neighborhood and chaos is introduced. The design method of FOPID controller using CNC-ABC algorithm for an AVR system is described in Section 3. The numerical results are given in Section 4. Finally, the concluding remarks are presented in Section 5.

1 Fractional calculus

Fractional calculus generalizes the ordinary calculus. The basic operation ${}_aD_t^\alpha$ is defined as:

$$
{}_aD_t^\alpha = \begin{cases} \dfrac{\mathrm{d}^\alpha}{\mathrm{d}t^\alpha}, & R(\alpha > 0) \\ 1, & R(\alpha = 0) \\ \displaystyle\int_a^t (\mathrm{d}t)^{-\alpha}, & R(\alpha < 0) \end{cases} \tag{1}
$$

where a and t are the lower and upper limits, α is the order of the operation[26] and it is a complex number, $R(\alpha)$ is the real part of α. Fractional derivative has several definitions. The usually used definitions are given by Riemann-Liouville (RL), Grü Nwald-Letnikor (GL) and Caputo. The RL definition is

$$
{}_aD_t^\alpha f(t) = \frac{1}{\Gamma(m-\alpha)}\left(\frac{\mathrm{d}}{\mathrm{d}t}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}}\mathrm{d}(\tau) \tag{2}
$$

where m is the first integer which is not less than α, i.e., $m - 1 < \alpha < m$. $\Gamma(\cdot)$ is famous Euler Gamma function. The GL definition is

$$
{}_aD_t^\alpha f(t) = \lim_{h\to 0} \frac{1}{\Gamma(\alpha)h^\alpha} \sum_{k=0}^{\frac{(t-\alpha)}{h}} \frac{\Gamma(k+\alpha)}{\Gamma(k+1)} f(t-kh) \tag{3}
$$

where h is the time increment.

Laplace transform is a popular tool in the analysis of control system. The Laplace transform of RL derivative under zero initial condition is

$$
L\{D^\alpha x(t)\} = s^\alpha X(s) \tag{4}
$$

2 CNC-ABC algorithm

2.1 Behavior of honey bees foraging

Bees are classical social insects. The behavior of only one bee is simple, however, a colony of bees manifest complicated intelligent behavior. In the real bee colony, the honey bees work in cooperation with appropriate division of labour. A minimal model of honey bees that can form swarm intelligence contains three elements: food source, employed bees and unemployed bees and three behaviors: exploring food source, recruiting bees for the food source and abandoning the food source.

The value of the food source is decided by several factors such as the distance to the beehive, the nectar amount and ease of extracting. For the sake of simplicity, it is represented as profitability with a simple quantity.

Employed bees are associated with a particular food source which they are currently exploiting or are "employed" at. They share the information of the food source by dancing in the dance area with a certain probability. The dance′s property is proportional to the profitability of the food source.

Unemployed bees are composed of onlookers and scouts. Scouts explore new food source randomly. The number of scouts averaged over conditions is about $5 \sim 10\,\%$[27]. When onlookers see the dances of employed bees, they estimate the profitability of the food sources and decide which one they will choose. So, more profitable food source recruits more onlookers to gather honey.

The behavior of honey bees foraging is shown as Fig. 1. Assuming there are two discovered food sources: A and B. At the beginning, a potential forager has no knowledge about the food sources as an unemployed bee. There are two choices for the bee:

1) It becomes a scout and explores new food source spontaneously around the nest (S in Fig. 1).

2) It becomes a recruit after watching the dances and starts searching for the food source (R in Fig. 1).

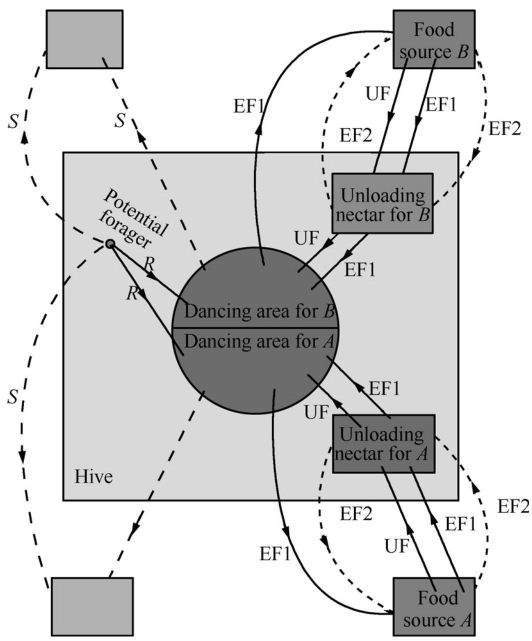

Fig. 1 Behavior of honey bee foraging

After locating the food source, the bee will start to exploit it and remember its situation. At this moment, the bee becomes an employed forager. When the bee returns to the hive carrying with nectar and unloads the nectar, it faces three choices:

1) It abandons the food source and becomes an onlooker (UF in Fig. 1);