Application of Cuckoo Search to Synthesize Analog Controllers

B. Wongkaew and D. Puangdownreong

***Abstract*—**In modern optimization, the CS was firstly proposed in 2009 to solve both continuous and combinatorial, single-objective and multi-objective optimization problems. It has been accepted and widely applied to solve several real-world engineering problems. In this paper, the CS is conducted to synthesize the analog controllers most commonly used in various control applications, i.e. Lead-Lag compensator, PID controller and PIDA controller. In this work, such the controllers are considered to be realized by analog electronic circuits using only one operational amplifier. The proposed synthesis approach can be determined as one of the constrained optimization problems. As results, it was found that the CS can effectively synthesize Lead-Lag compensator, PID controller, and PIDA controller satisfying to the predefined objective and constrained functions.

***Keywords*—**Cuckoo search, Lead-Lag compensator, PID controller, PIDA controller, Metaheuristics.

I. Introduction

TO-DATE, metaheuristic optimization algorithms have become more and more popular in engineering applications and other optimization problems. This is because they rely on rather simple concepts and easy to implement based on randomly searching approach. They do not require gradient information and can escape local entrapments. Finally, they can be applied in a wide range of problems covering different disciplines [1],[2]. By literatures, mostly nature-inspired metaheuristic algorithms are developed by mimicking biological or physical phenomena. They can be grouped in four main categories: (i) evolution-based, (ii) physics-based, (iii) bio-swarm-based and (iv) human-based metaheuristic algorithms. The most popular evolution-based algorithms are Genetic Algorithms (GA) [3] and Differential Evolution (DE) [4]. The most well-known physics-based algorithms are Simulated Annealing (SA) [5] and Big-Bang Big-Crunch (BBBC) [6]. Many bio-swarm-based algorithms are most popular, for instance, Particle Swarm Optimization (PSO) [7], Ant Colony Optimization (ACO) [8], Bat-inspired Algorithm (BA) [9], Firefly Algorithm (FA) [10], Hunting Search (HS) [11], Grey Wolf Optimizer (GWO) [12], Whale Optimization Algorithm (WOA) [13] Cuckoo Search (CS) [14] and Flower Pollination Algorithm (FPA) [15]. For the last group, the most popular human-based algorithms are Tabu Search (TS) [16] and Harmony Search (HS) [17].

Among those, the CS is one of the most popular and efficient for solving both continuous and combinatorial, single-objective and multi-objective optimization problems. The CS, firstly proposed by Yang and Deb in 2009 [14], possesses only two main search parameters for fine adjustment. Also, it was proved for the global convergent property [18] and successfully applied to many real-world engineering problems, for example, wind turbine blades [19], antenna arrays [20], power systems [21], travelling salesman problem [22], structural optimization problem [23], wireless sensor network [24], flow shop scheduling problem [25], job shop scheduling problem [26] and control systems [27]. The state-of-the-art and its applications of the CS have been reviewed and reported [28].

From our previous work, the CS was applied to synthesize an analog PID controller based on only one operational amplifier (op-amp) circuit [29]. To extend the frontier of the metaheuristics-based synthesis applications, the CS is then applied in this paper to synthesize Lead-Lag compensator, PID controller and PIDA controller. Such the controllers are still realized by using only one op-amp circuit which is more complex than using many op-amps. After an introduction is presented in section I, the rest of the paper is arranged as follows. The CS algorithms, problem formulation, results and discussions, and conclusions are given in section II, III, IV and V, respectively.

II. Cuckoo Search Algorithms

The Cuckoo Search (or CS) was firstly introduced by Yang and Deb in 2009 [14] based on an inspiration from the brooding parasitism of cuckoo species in nature associated with Lévy distribution. From preliminary studies of Yang and Deb [14],[30] against well-known benchmark functions to perform its effectiveness, it was found that the CS showed promising results outperforming GA and PSO. The CS has been applied in almost every area and domain of function optimization, engineering optimization, image processing, scheduling, planning, feature selection, forecasting and real-world applications [28].

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In CS algorithms, there are two essential parameters: number of cuckoos (n) and a fraction p_a denoting the ability of host birds that can find the cuckoos' eggs. New solutions $\boldsymbol{x}^{(t+1)}$ for cuckoo i can be generated by Lévy distribution as expressed in (1), where a symbol Lévy(λ) represents the Lévy distribution having an infinite variance with an infinite mean as expressed in (2). The step length s of cuckoo flight can be obtained by (3), where u and v stand for normal distribution as stated in (4). Standard deviations of u and v are also expressed in (5). The CS algorithms can be represented by the flow diagram shown in Fig.1.

$$\boldsymbol{x}_i^{(t+1)} = \boldsymbol{x}_i^{(t)} + \alpha \oplus \text{Lévy}(\lambda) \tag{1}$$

$$\text{Lévy} \approx u = t^{-\lambda}, \quad (1 < \lambda \le 3) \tag{2}$$

$$s = \frac{u}{|v|^{1/\beta}} \tag{3}$$

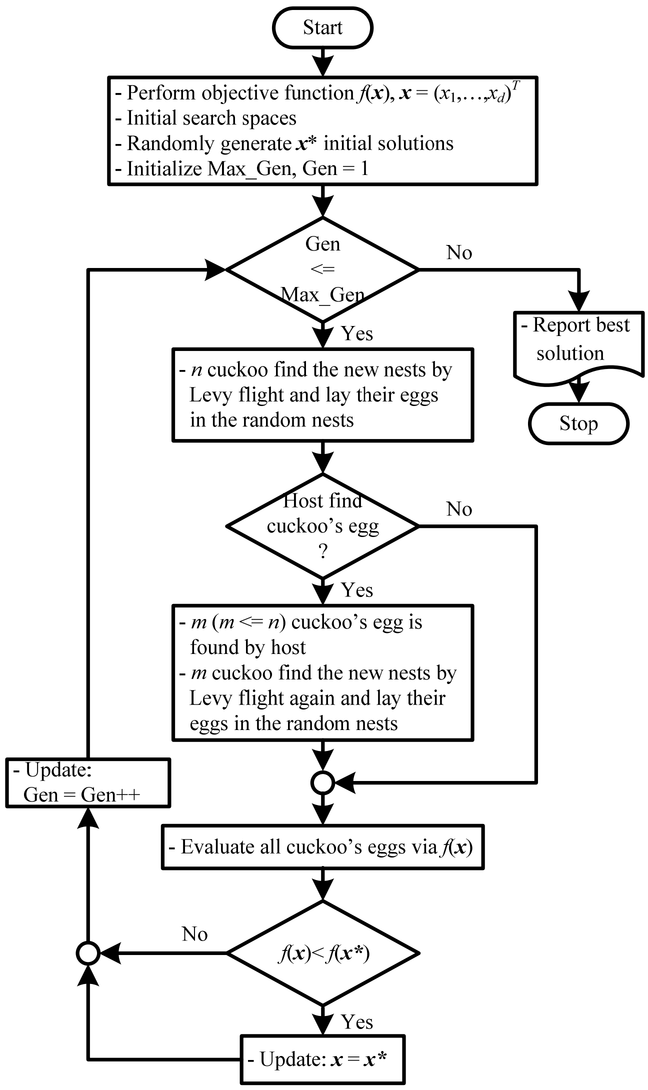

Fig. 1 flow diagram of CS algorithms

$$u \approx N(0.\, \sigma_u^2), \quad v \approx N(0.\, \sigma_v^2) \tag{4}$$

$$\sigma_u = \left\{ \frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}} \right\}^{1/\beta}, \quad \sigma_v = 1 \tag{5}$$

III. Problem Formulation

In this section, the problem formulation is proposed. The mathematical models of Lead-Lag compensator, PID controller and PIDA controller and their correspondingly analog electronic circuits using only one op-amp for realization are firstly given. Then, the CS-based analog controller synthesis is followed.

A. Lead-Lag Compensator

In the classical control system, the mathematical formulation of the Lead-Lag compensator is expressed by s-domain transfer function as stated in (6), where K_c is compensator gain, T_1, T_2, $\gamma > 1$ and $\beta > 1$are pole and zero factors of compensator.

$$\left. \begin{aligned} G_c(s)\big|_{Lead-Lag} &= K_c \frac{\beta}{\gamma}\left(\frac{T_1 s+1}{T_1 s/\gamma+1}\right)\left(\frac{T_2 s+1}{\beta T_2 s+1}\right) \\ &= K_c \frac{(s+1/T_1)(s+1/T_2)}{(s+\gamma/T_1)(s+1/\beta T_2)} \end{aligned} \right\} \tag{6}$$

The Lead-Lag compensator employing only one op-amp circuit is represented in Fig. 2 [31]. Here, the right-hand side op-amp (INV) is uncounted because it stands for an inverting amplifier having gain of –1. The transfer function $E_o(s)/E_i(s)$ of the op-amp circuit in Fig. 2 is shown in (7). Once comparing (6) and (7), mathematical relations in (8) can be performed.

$$\frac{E_o(s)}{E_i(s)} = \frac{R_4}{R_3}\left(\frac{[(R_1+R_3)C_1 s+1](R_2 C_2 s+1)}{(R_1 C_1 s+1)[(R_2+R_4)C_2 s+1]}\right) \tag{7}$$

$$\left. \begin{aligned} & K_c = \frac{R_2 R_4}{R_1 R_3}\left(\frac{R_1+R_3}{R_2+R_4}\right), \\ & \gamma = \frac{R_1+R_3}{R_1} > 1, \\ & \beta = \frac{R_2+R_4}{R_2} > 1, \\ & T_1 = (R_1+R_3)C_1, \quad T_2 = R_2 C_2 \end{aligned} \right\} \tag{8}$$

B. PID Controller

The mathematical formulation of the PID controller in a form of s-domain transfer function is stated in (9), where K_p, K_i and K_d are proportional, integral and derivative gains, respectively.

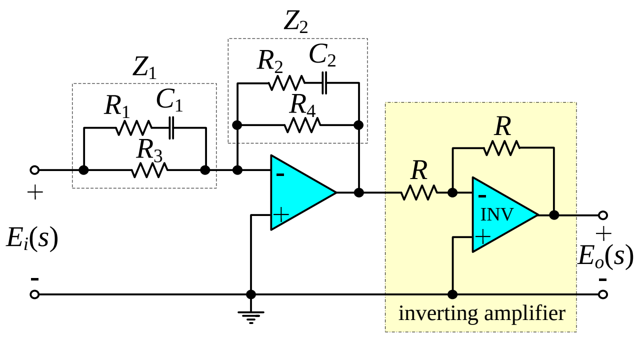

Fig. 2 analog lead-lag compensator

$$G_c(s)\big|_{PID} = K_p + \frac{K_i}{s} + K_d s \tag{9}$$

The PID controller employing only one op-amp circuit is represented in Fig. 3 [31]. As the analog Lead-Lag compensator in Fig. 2, the right-hand side op-amp (INV) is uncounted because it stands for an inverting amplifier having gain of –1. The transfer function $E_o(s)/E_i(s)$ of the circuit in Fig. 3 is shown in (10). When comparing (9) and (10), mathematical relations in (11) can be obtained.

$$\frac{E_o(s)}{E_i(s)} = \frac{R_2}{R_1}\left(\frac{R_1C_1 + R_2C_2}{R_2C_2} + \frac{1}{R_2C_2 s} + R_1C_1 s\right) \tag{10}$$

$$\left.\begin{aligned} K_p &= \frac{R_1C_1 + R_2C_2}{R_1C_2}, \\ K_i &= \frac{1}{R_1C_2}, \quad K_d = R_2C_1 \end{aligned}\right\} \tag{11}$$

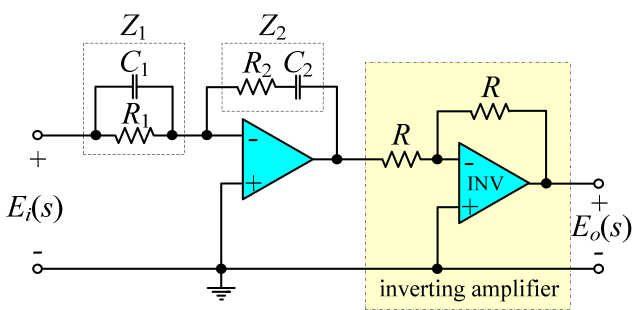

Fig. 3 analog PID controller

C. PIDA Controller

The mathematical formulation of the PIDA controller in s-domain transfer function is expressed in (12), where K_p, K_i, K_d and K_a are proportional, integral, derivative and accelerated gains, respectively.

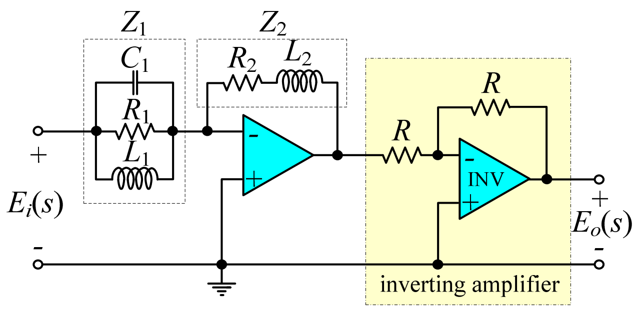

Fig. 4 analog PIDA controller

$$G_c(s)\big|_{PIDA} = K_p + \frac{K_i}{s} + K_d s + K_a s^2 \tag{12}$$

The PIDA controller employing only one op-amp circuit is proposed in Fig. 4. As the analog Lead-Lag compensator in Fig. 2 and the analog PID controller in Fig. 3, the right-hand side op-amp (INV) is uncounted because it stands for an inverting amplifier having gain of –1. The transfer function $E_o(s)/E_i(s)$ of the op-amp circuit in Fig. 4 is formulated as stated in (13). When comparing (12) and (13), mathematical relations in (14) can be provided.

$$\frac{E_o(s)}{E_i(s)} = \frac{\left(\begin{aligned} R_1L_1L_2C_1s^3 + L_1(R_1R_2C_1 + L_2)s^2 \\ + (R_1L_2 + R_2L_1)s + R_1R_2 \end{aligned}\right)}{R_1L_1s} \tag{13}$$

$$\left.\begin{aligned} K_p &= \frac{R_1L_2 + R_2L_1}{R_1L_1}, \quad K_i = \frac{R_2}{L_1}, \\ K_d &= \frac{R_1R_2C_1 + L_2}{R_1}, \quad K_a = L_2C_1 \end{aligned}\right\} \tag{14}$$

D. CS-Based Analog Controller Synthesis

In this work, Lead-Lag compensator, PID controller and PIDA controller are assumed to de already designed. Such the controller (or compensator) will be synthesized by using only one op-amp circuit. As the constrained optimization problem, the objective functions $f(\cdot)$ for the CS-based controller synthesis are set for Lead-Lag compensator, PID controller and PIDA controller as shown in (15), (17) and (19), respectively, for minimization. The normal parameters without (^) are the controllers' parameters already obtained by the particular design methods, while the parameters with (^) are the controllers' parameters obtained by the CS. The constrained functions $g(\cdot)$ for Lead-Lag compensa-tor, PID controller and PIDA controller are also set as expressed in (16), (18) and (20), respectively, where $R_{n\_\min}$ and $R_{n\_\max}$ are lower and upper bounds of R_n, $L_{n\_\min}$ and $L_{n\_\max}$ are lower and upper bounds of L_n and $C_{n\_\min}$ and $C_{n\_\max}$ are lower and upper bounds of C_n, respectively. All objective functions will be minimized to satisfy the correspondingly constrained functions by CS's searching for the appropriate values of R_n, L_n and C_n in each circuit.

$$\textbf{Min} \quad f_{Lead-Lag}(\cdot) = \frac{(K_c - \hat{K}_c)^2}{K_c} + \frac{(\gamma - \hat{\gamma})^2}{\gamma} + \frac{(\beta - \hat{\beta})^2}{\beta} + \frac{(T_1 - \hat{T}_1)^2}{T_1} + \frac{(T_2 - \hat{T}_2)^2}{T_2} \tag{15}$$

$$\text{Subject to} \quad \left. \begin{aligned} & g_1 : R_{1\min} \le R_1 \le R_{1\max}, \\ & g_2 : R_{2\min} \le R_2 \le R_{2\max}, \\ & g_3 : R_{3\min} \le R_3 \le R_{3\max}, \\ & g_4 : R_{4\min} \le R_4 \le R_{4\max} \\ & g_5 : C_{1\min} \le C_1 \le C_{1\max}, \\ & g_6 : C_{2\min} \le C_2 \le C_{2\max}, \\ & g_7 : (R_1 + R_3)/R_1 > 1, \\ & g_8 : (R_2 + R_4)/R_2 > 1 \end{aligned} \right\} \tag{16}$$

$$\textbf{Min} \quad f_{PID}(\cdot) = \frac{(K_p - \hat{K}_p)^2}{K_p} + \frac{(K_i - \hat{K}_i)^2}{K_i} + \frac{(K_d - \hat{K}_d)^2}{K_d} \tag{17}$$

$$\text{Subject to} \quad \left. \begin{aligned} & g_1 : R_{1\min} \le R_1 \le R_{1\max}, \\ & g_2 : R_{2\min} \le R_2 \le R_{2\max}, \\ & g_3 : C_{1\min} \le C_1 \le C_{1\max}, \\ & g_4 : C_{2\min} \le C_2 \le C_{2\max} \end{aligned} \right\} \tag{18}$$

$$\textbf{Min} \quad f_{PIDA}(\cdot) = \frac{(K_p - \hat{K}_p)^2}{K_p} + \frac{(K_i - \hat{K}_i)^2}{K_i} + \frac{(K_d - \hat{K}_d)^2}{K_d} + \frac{(K_a - \hat{K}_a)^2}{K_a} \tag{19}$$

$$\text{Subject to} \quad \left. \begin{aligned} & g_1 : R_{1\min} \le R_1 \le R_{1\max}, \\ & g_2 : R_{2\min} \le R_2 \le R_{2\max}, \\ & g_3 : L_{1\min} \le L_1 \le L_{1\max}, \\ & g_4 : L_{2\min} \le L_2 \le L_{2\max} \\ & g_5 : C_{1\min} \le C_1 \le C_{1\max} \end{aligned} \right\} \tag{20}$$

IV. Results and Discussions

In order to synthesize Lead-Lag compensator, PID controller and PIDA controller, the CS algorithms were coded by MATLAB version 2017b (License No.#40637337) run on Intel(R) Core(TM) i5-3470 CPU@3.60GHz, 4.0GB-RAM.

The CS parameters are set according to recommendations of Yang and Deb [14],[30]: number of cuckoos (n = 40) and a fraction p_a = 0.2 (or 20%). 50 trials are conducted for all cases to find the best solution.

A. *Case-I (Lead-Lag Compensator)*

The ready-designed Lead-Lag compensator is stated in (21) [31]. Lower and upper bounds of each element in the circuit shown in Fig. 2 are set according to available low-cost resistors and capacitors as expressed in (22) which are possible to be implemented. The maximum generation *MaxGen* = 50 is then set as the termination criteria (TC) for this case. The CS can successfully provide the optimal values of R_1, R_2, R_3, R_4, C_1 and C_2 of the analog Lead-Lag compensator shown in Fig. 2 as stated in (23) within the average search time of 1.3712 sec. The convergent rates of the objective function in (15) associated with the constraints in (16) of this case proceeded by the CS are depicted in Fig. 5.

$$G_c(s)\big|_{Lead-Lag} = \frac{6.26(s+0.5)(s+0.2)}{(s+5.02)(s+0.01247)} \tag{21}$$

$$\left. \begin{aligned} & [R_{1\min}, R_{1\max}] = [0\ \Omega, 1\ \mathrm{M}\Omega], \\ & [R_{2\min}, R_{2\max}] = [0\ \Omega, 1\ \mathrm{M}\Omega], \\ & [R_{3\min}, R_{3\max}] = [0\ \Omega, 1\ \mathrm{M}\Omega], \\ & [R_{4\min}, R_{4\max}] = [0\ \Omega, 1\ \mathrm{M}\Omega], \\ & [C_{1\min}, C_{1\max}] = [0\ \mathrm{F}, 1\ \mathrm{mF}], \\ & [C_{2\min}, C_{2\max}] = [0\ \mathrm{F}, 1\ \mathrm{mF}] \end{aligned} \right\} \tag{22}$$

$$\left. \begin{aligned} & R_1 = 15.52\ \mathrm{K}\Omega, \quad R_2 = 101.17\ \mathrm{K}\Omega, \\ & R_3 = 233.40\ \mathrm{K}\Omega, \quad R_4 = 914.55\ \mathrm{K}\Omega, \\ & C_1 = 8.03\ \mu\mathrm{F}, \quad C_2 = 49.442\ \mu\mathrm{F} \end{aligned} \right\} \tag{23}$$

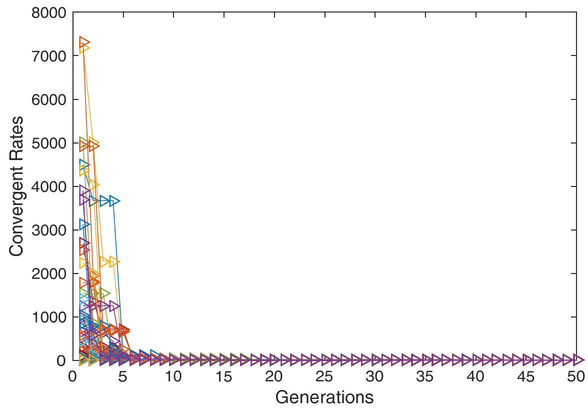

Fig. 5 convergent rates of case-I over 50 trials

B. *Case-II (PID Controller)*

The ready-designed PID controller is given in (24) [29]. Lower and upper bounds of each element in the circuit shown in Fig. 3 are set according to available low-cost resistors and capacitors as expressed in (25). The *MaxGen* = 2,000 is then set as the TC for this case. The CS can successfully provide the optimal values of R_1, R_2, C_1 and C_2 of the analog PID controller shown in Fig. 3 as stated in (26) within the average search time of 2.5170 sec. The convergent rates of the objective function in (17) associated with its constraints in (18) of this case proceeded by the CS are plotted in Fig. 6.

$$G_c(s)\big|_{PID} = 4{,}914.53 + \frac{16{,}284.08}{s} + 371.05s \tag{24}$$

$$\left.\begin{aligned} &[R_{1\min}, R_{1\max}] = [0\ \Omega, 10\ \text{K}\Omega],\\ &[R_{2\min}, R_{2\max}] = [0\ \Omega, 10\ \text{K}\Omega],\\ &[C_{1\min}, C_{1\max}] = [0\ \text{F}, 1\ \text{F}],\\ &[C_{2\min}, C_{2\max}] = [0\ \text{F}, 1\ \text{F}] \end{aligned}\right\} \tag{25}$$

$$\left.\begin{aligned} &R_1 = 0.49\ \Omega, \quad R_2 = 1.20\ \text{K}\Omega,\\ &C_1 = 0.31\ \text{F}, \quad C_2 = 0.13\ \text{mF} \end{aligned}\right\} \tag{26}$$

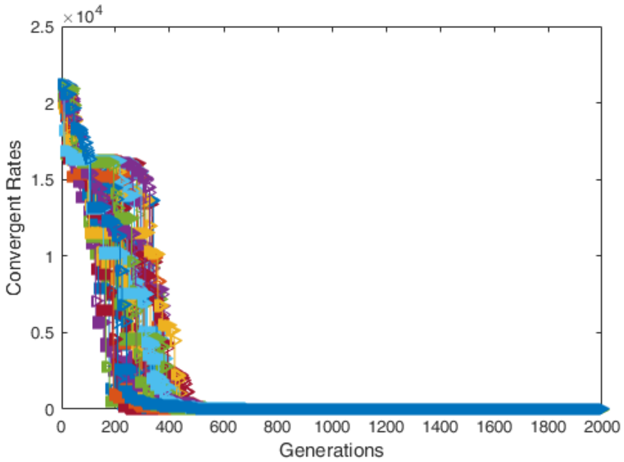

Fig. 6 convergent rates of case-II over 50 trials

C. *Case-III (PIDA Controller)*

The ready-designed PIDA controller is given in (27) [32]. Lower and upper bounds of each element in the circuit shown in Fig. 4 are set according to available low-cost resistors, inductors and capacitors as expressed in (28). The *MaxGen* = 500 is then set as the TC for this case. The CS can successfully provide the optimal values of R_1, R_2, L_1, L_2 and C_1 of the analog PIDA controller shown in Fig. 4 as stated in (29) within the average search time of 0.6523 sec. The convergent rates of the objective function in (19) associated with its constraints in (20) of this case proceeded by the CS are plotted in Fig. 7.

$$G_c(s)\big|_{PIDA} = 25.03 + \frac{3.04}{s} + 9.98s + 3.01s^2 \tag{27}$$

$$\left.\begin{aligned} &[R_{1\min}, R_{1\max}] = [0\ \Omega, 10\ \text{K}\Omega],\\ &[R_{2\min}, R_{2\max}] = [0\ \Omega, 10\ \text{K}\Omega],\\ &[L_{1\min}, L_{1\max}] = [0\ \text{H}, 10\ \text{H}],\\ &[L_{2\min}, L_{2\max}] = [0\ \text{H}, 10\ \text{H}],\\ &[C_{1\min}, C_{1\max}] = [0\ \text{F}, 1\ \text{F}] \end{aligned}\right\} \tag{28}$$

$$\left.\begin{aligned} &R_1 = 0.82\ \Omega, \quad R_2 = 1.00\ \Omega,\\ &L_1 = 0.33\ \text{H}, \quad L_2 = 7.88\ \text{H},\\ &C_1 = 0.38\ \text{F} \end{aligned}\right\} \tag{29}$$

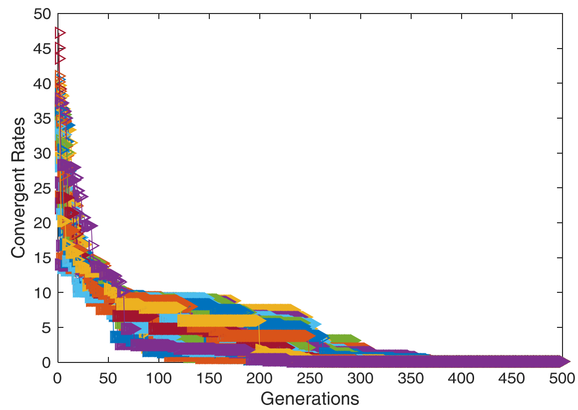

Fig. 7 convergent rates of case-III over 50 trials

V. Conclusions

The application of the cuckoo search (CS) to synthesize the analog controllers, i.e. Lead-Lag compensator, PID controller and PIDA controller, has been proposed in this paper. Such the controllers have been assumed to be realized by analog electronic circuits using only one operational amplifier (op-amp). Considered as the constrained optimization problems, it was found that the CS could successfully provide the optimal values of circuit's elements to perform the Lead-Lag compensator, PID controller and PIDA controller. The circuit's elements, i.e. resistors, inductors and capacitors, obtained by the CS are available and possible to implement the analog Lead-Lag compensator, PID controller and PIDA controller using only one op-amp circuit. This can be noted that any ready-designed controller by the particular design method can be synthesized to be analog controller by the proposed CS-based synthesis framework.

References

[1] E. G. Talbi, *Metaheuristics form Design to Implementation*, John Wiley & Sons, 2009.

[2] F. Glover and G.A. Kochenberger, *Handbook of Metaheuristics*, Kluwer Academic Publishers, 2003.

[3] D. E. Goldberg, *Genetic Algorithm in Search, Optimization, and Machine Learning*, Addison-Wesley Publishing, 1989.

[4] K. V. Price, R. M. Storn and J. A. Lampinen, *Differential Evolution: A Practical Approach to Global Optimization*, Springer, 2006.
[5] S. Kirkpatrick, C. D. Gelatt, M. P. Vecchi, "Optimization by simulated annealing," *Science*, vol. 220, pp. 671-680, 1983.
[6] O. K. Erol and I. A. Eksin, "A new optimization method: big bang–big crunch," *Advances in Engineering Software*, vol. 37, pp. 106–111, 2006.
[7] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. 1995 IEEE International Conference on Neural Networks*, pp. 1942–1948, 1995.
[8] M. Dorigo, M. Birattari and T. Stutzle, "Ant colony optimization," *IEEE Transactions on Computer Intelligence*, vol. 1, pp. 28–39, 2006.
[9] X. S. Yang, "A new metaheuristic bat-inspired algorithm," *Nature Inspired Cooperative Strategies for Optimization (NISCO 2010) (Eds. J. R. Gonzalez et al.), Studies in Computational Intelligence*, Springer Berlin, vol. 284, pp. 65–74, 2010.
[10] X. S. Yang, "Firefly algorithms for multimodal optimization," *Stochastic Algorithms: Foundations and Applications, SAGA 2009, Lecture Notes in Computer Sciences*, vol. 5792, pp. 169–178, 2009.
[11] R. Oftadeh, M. J. Mahjoob and M. Shariatpanahi, "A novel meta-heuristic optimization algorithm inspired by group hunting of animals: hunting search," *Computers and Mathematics with Applications*, vol. 60, pp. 2087–2098, 2010.
[12] S. Mirjalili, S. M. Mirjalili and A. Lewis, "Grey wolf optimizer," *Advances in Engineering Software*, vol. 69, pp. 46–61, 2014.
[13] S. Mirjalili and A. Lewis, "The whale optimization algorithm," *Advances in Engineering Software*, vol. 95, pp. 51–67, 2016.
[14] X. S. Yang and S. Deb, "Cuckoo search via Lévy flights," in *Proc. World Congress on Nature & Biologically Inspired Computing (NaBIC 2009)*, pp. 210–214, 2009.
[15] X. S. Yang, "Flower pollination algorithm for global optimization," *Unconventional Computation and Natural Computation, Lecture Notes in Computer Science*, vol. 7445, 240–249, 2012.
[16] F. Glover and M. Laguna, *Tabu Search*, Kluwer Academic Publishers, 1997.
[17] Z. W. Geem, J. H. Kim and G. Loganathan, "A new heuristic optimization algorithm: harmony search," *Simulation*, vol. 76, pp. 60–68, 2001.
[18] X. S. Yang, "Cuckoo search and firefly algorithm: overview and analysis," *Studied in Computational Intelligence: Cuckoo search and Firefly Algorithm Theory and Applications*, Springer, pp. 1–26, 2014.
[19] B. Ernst, M. Bloh, J. R. Seume and A. G. González, "Implementation of the cuckoo search algorithm to optimize the design of wind turbine rotor blades," in *Proc. European Wind Energy Association (EWEA) 2012*, 2012.
[20] M. Khodier, "Optimisation of antenna arrays using the cuckoo search algorithm," *IET Microwaves, Antennas & Propagation*, vol. 7, no. 6, pp. 458–464, 2013.
[21] S. Rangasamy and P. Manickam, "Stability analysis of multimachine thermal power systems using nature inspired modified cuckoo search algorithm," *Turkish Journal of Electrical Engineering & Computer Sciences*, DOI: 10.3906/elk-1212-39, 2013.
[22] A. Ouaarab, B. Ahiod and X. S. Yang, "Discrete cuckoo search algorithm for the travelling salesman problem," *Neural Computing and Applications*, pp. 1–11, 2013.
[23] A. H. Gandomi, X. S. Yang and A. H. Alavi, "Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems," *Engineering with computers*, vol. 29, no. 1, pp. 17–35, 2013.
[24] M. Dhivya and M. Sundarambal, "Cuckoo search for data gathering in wireless sensor networks", *International Journal of Mobile Communications*, vol. 9, no. 6, pp. 642–656, 2011.
[25] M. K. Marichelvam, "An improved hybrid cuckoo search (ihcs) metaheuristics algorithm for permutation flow shop scheduling problems," *International Journal of Bio-Inspired Computation*, vol. 4, no. 4, pp. 200–205, 2012.
[26] S. Hanoun, S. Nahavandi, D. Creighton and H. Kull, "Solving a multiobjective job shop scheduling problem using pareto archived cuckoo search, in *Proc. 17th IEEE Conference on Emerging Technologies & Factory Automation (ETFA)*, pp. 1–8, 2012.
[27] D. Puangdownreong, A. Nawikavatan and C. Thammarat, "Optimal design of I–PD controller for DC motor speed control system by cuckoo search," *Procedia Computer Science*, vol. 86, pp. 83–86, 2016.
[28] I. Fister Jr., X. S. Yang, D. Fister and I. Fister, "Cuckoo search: a brief literature review," *Cuckoo Search and Firey Algorithm: Theory and Applications, Studies in Computational Intelligence*, vol. 516, pp. 49–62, 2014.
[29] D. Puangdownreong, B. Wongkaew, C. Thammarat and S. Hlungnamthip, Synthesis of analog PID controller via cuckoo search, in *Proc. the 2018 International Conference on Engineering and Natural Science (ICENS 2018)*, pp. 43–50, 2018.
[30] X. S. Yang and S. Deb, Engineering Optimisation by Cuckoo Search, *Mathematical Modelling and Numerical Optimisation*, vol. 1, no. 4, pp. 330–343, 2010.
[31] K. Ogata, *Modern Control Engineering*, 5th-edition, Pearson Prentice Hall, 2010.
[32] A. Nawikavatan, T. Jitwang, C. Thammarat and D. Puangdownreong, Application of cuckoo search to optimal PIDA controller design for three-tank liquid-level control system, in *Proc. the 2018 International Conference on Engineering and Natural Science (ICENS 2018)*, pp. 51–59, 2018.

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