1. Abdulla I. Abdulla[1], 2. Mohammed Almaged[2], 3. Salam Ibrahim khather[3]

Ninevah University (1,2,3)

ORCID. 1. 0000-0003-4025-3478, 2. 0000-0003-3060-9266, 3. 0000-0002-9082-2360

doi:10.15199/48.2022.03.18

Aircraft Pitch Angle Control Using Pole Placement Approach Based on GA and ABC Optimization Techniques

***Abstract**. The main objective of the present work is designing a pole placement controller for pitch angle control of an aircraft system based on several bio-inspired optimization methods. Initially, a mathematical model of an aircraft pitch system has been derived and formed in state space representation. Then, pole placement approach is designed with the aid of different optimization techniques, including Genetic Algorithms (GA) and Artificial Bee Colony (ABC), to find an optimal value for the feedback gain matrix. The goal is to choose an optimal target values for the closed loop poles of the system by state feedback method and place them at every targeted location anywhere in the left-half of the complex plane ensuring that the closed-loop poles are stable and controllable. This work also compares the performance of GA with that of ABC algorithm based on different time response characteristics. The efficiency of the control systems responses has been analyzed for the sake of deciding which optimization approach will produce better results concerning the controlled pitch angle. Based on the obtained simulation results, it has been noted that ABC based pole placement controller exhibited more efficient results and overweigh the performance of pole placement controllers based on GA.*

Streszczenie. Głównym celem niniejszej pracy jest zaprojektowanie kontrolera rozmieszczenia biegunów do sterowania kątem pochylenia systemu samolotu w *oparciu o kilka metod optymalizacji inspirowanych biologią. Początkowo opracowano model matematyczny układu nachylenia samolotu i utworzono go w reprezentacji w przestrzeni stanów. Następnie projektuje się podejście do umieszczania tyczek za pomocą różnych technik optymalizacji, w tym algorytmów genetycznych (GA) i sztucznej kolonii pszczół (ABC), aby znaleźć optymalną wartość macierzy wzmocnienia sprzężenia zwrotnego. Celem jest wybór optymalnych wartości docelowych dla biegunów pętli zamkniętej systemu metodą sprzężenia zwrotnego stanu i umieszczenie ich w każdym docelowym miejscu w dowolnym miejscu w lewej połowie złożonej płaszczyzny, zapewniając stabilność i kontrolę biegunów pętli zamkniętej. Ta praca porównuje również wydajność GA z wydajnością algorytmu ABC w oparciu o różne charakterystyki czasowe odpowiedzi. Skuteczność odpowiedzi układów sterowania została przeanalizowana w celu określenia, które podejście optymalizacyjne przyniesie lepsze wyniki w zakresie kontrolowanego kąta pochylenia. Na podstawie uzyskanych wyników symulacji zauważono, że sterownik układania słupów oparty na ABC wykazał bardziej wydajne wyniki i przewyższał wydajność sterowników układania słupów opartych na GA.* (***Kontrola kąta pochylenia statku powietrznego przy użyciu podejścia polegającego na umieszczeniu słupa w oparciu o techniki optymalizacji GA i ABC***)

Keywords: Aircraft Pitch Control; Pole Placement; GA; ABC
Słowa kluczowe: kontrola nachylenia samolotu, algorytm generyczny.

Introduction

The combination of modeling nonlinearities, parameters uncertainty and variation are the main difficulties of flight control system [1]. In general, basic flight system is controlled using three fundamental surfaces. Those surfaces are the elevator ailerons and rudder. It is possible to achieve pitch control via altering the lift of the elevator tail surface while to achieve a yaw control, deflection of a flap on vertical tail of the rudder must be performed which is placed outboard in the direction of wing tips in a differential way. However, to change the bank angle of the aircraft, small flaps deflection of the ailerons which is located on the main wings is necessary to roll the aircraft [2]. An aircraft's pitch control is achieved through the adjustment of the pitch angle. Beside aerodynamic design, aircraft systems depends greatly on the designed control system to effectively navigate in the air. The development of flight control system has drawn a great attention in the area of both commercial and military aviation. Modern aircraft contains several intelligent control subsystems which assists the flight pilots in navigation, improving stability and rejecting sudden disturbance during harsh weather condition [3-6].

Pole placement is a control method at which the closed loop eigenvalues, which have a great influence on stability, steady state and transient response performance, are assigned to specified position in a complex plane by state or output feedback. This technique has emerged with many significant features because of its straightforward algorithmic structure. Pole placement approach is one of the commonly applied techniques in different control system applications. In 2012, Naimul Hasan [7] applied this technique interconnected power systems. The analysis of the obtained results proved that the performance of the regulators designed using pole placement overweigh other techniques. In the same vein, Eshtehardiha et al. [8] employed genetic algorithm-based pole placement approach to control the operation of buck converters. This controller also proved its ability of regulating nonlinear dynamic system. In their work, Yan Lan and Fei Minrui [9] proposed a state-space pole-placement controller for a non-linear double-parallel inverted pendulum. Similarly, the validity of this technique is examined using a control-oriented model introduced to mimic a wide range of digital nonlinear dynamic systems [10]. All the closed loop poles of the system can be placed in the complex plane through the state feedback matrix. However, only part of the poles is required to be moved to predefined locations because of their associated instability and oscillations. A group of researchers [11] developed a modified pole placement algorithm that only moves these undesired poles to pre-defined positions within the stability zone.

In this article, Genetic Algorithm (GA) and Artificial Bee Colony (ABC) are implemented for placement optimization of the system poles for the improvement of pitch angle response. GA was first introduced by J. Holland in 1970 to enhance the characteristic operation of computational based approaches. It begins without any information about the proper solution. Instead, it randomly starts generating responses through modifying several genetic operators such as selection, mutation, and crossover to obtain the finest solution. It initiates searching with many independent random points in parallel to avoid local minima and thus the algorithm converges to sub-optimal solutions [12]. The ABC was initially proposed and implemented successfully to different fields by Karaboga in 2005 [13]. This optimization technique is based on a particular intelligent foraging of honeybee swarms. In this approach, the honey bees swarm is classified into three groups that are employee bees, onlooker bees, and last scout bees. The employee bees have the same size as that of onlooker bees and it is equivalent to half colony size. The ABC algorithm ought weigh the performance of other algorithms based on population search with the benefits of utilizing less control parameters [13, 14]. Because of its simple structure and direct implementation, ABC algorithm has drawn great attention and has been employed to optimize different control problems. However, like other evolutionary algorithms, ABC also has some drawbacks which affects its performance [15].

In the present research, the dynamic modeling of flight system is considered in the design process of an autopilot pitch angle control of an aircraft. Then, ABC and GA based pole placement controller have been introduced for aircraft systems pitch control. Finally, the responses of the designed control systems are examined and evaluated based on several measures of time response characteristics to find out which optimization technique gives a better result with respect to the required pitch angle.

Aircraft Modeling

The model of Aircraft systems is quite complex that requires a group of highly nonlinear differential equations. Yet taken particular assumptions, these equations are simplified and then linearized into several lateral and longitudinal sets of equations. The moments, forces, and velocity components of aircraft body system is shown in figure 1.

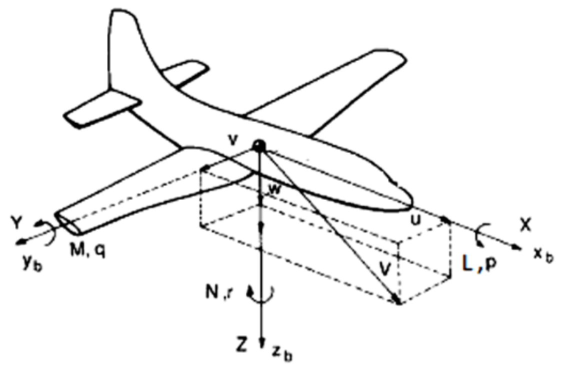


Fig.1. Forces, moments and velocity components of aircraft system.

The aerodynamics force components are represented by Xb, Yb and Zb, while the aerodynamic moment components are denoted by L, M and N in the earth-axis system. The symbols q, p and r express the components of angular rates for the pitch, roll and yaw axis while the velocity components of pitch, roll and yaw frame are stated as v, u and w. The longitudinal equations of motion in the pitch direction can be represented in state space form as follow [4, 16]:

$$\begin{bmatrix}\dot{w}\\ \dot{q}\\ \dot{\theta}\end{bmatrix}=\begin{bmatrix}\frac{Z_w}{m} & u_0 & -g\sin\theta 0\\ \frac{M_w+Z_w\frac{M_{\dot{w}}}{m}}{I_{yy}} & \frac{M_q+mu_0\frac{M_{\dot{w}}}{m}}{I_{yy}} & \frac{-mg\sin\theta 0}{I_{yy}}\frac{M_{\dot{w}}}{m}\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}w\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}\frac{Z_{\delta_e}}{m-Z_{\dot{w}}}\\ \frac{M_{\delta_e}+Z_{\delta_e}}{I_{yy}}\\ 0\end{bmatrix}\delta_e$$

The terms θ and δ_e represent the aircraft pitch and elevator deflection angles respectively. In this work, the data from [16] is implemented in system modeling and analysis. After plugging the numerical values, the state space representation of the aircraft pitch subsystem is given as follow:

$$\begin{bmatrix}\dot{w}\\ \dot{q}\\ \dot{\theta}\end{bmatrix}=\begin{bmatrix}-0.3149 & 235.8928 & 0\\ -0.0034 & -0.4282 & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}w\\ q\\ \theta\end{bmatrix}+\begin{bmatrix}-5.5079\\ 0.0021\\ 0\end{bmatrix}\delta_e$$

$$y=[\,0\;0\;1]\begin{bmatrix}w\\ q\\ \theta\end{bmatrix}+[0]$$

Pole Placement Controller Design

The location of the closed-loop poles of the system determines the stability and various time domain specifications. Thus, pole placement control system design is a process that ensure locating those poles at the best positions which produce rational and desired performance. State feedback approach has been applied widely in producing optimal control law and rejecting disturbance influence [9]. The pole-placement approach is utilized to locate the closed-loop poles of the system at the preferred positions via state feedback technique. The main steps to carry out in the design process of pole placement controller is the assignment of suitable feedback gain matrix that ensure the stability of the system and meet the desired specifications [17].

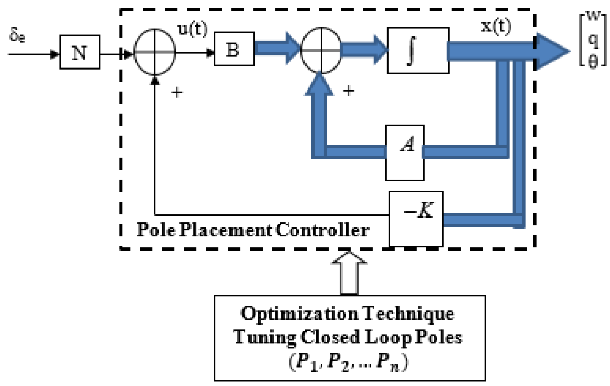


Fig. 2. Structure of optimized pole-placement controller.

For a given system represented in state space form, the Pole-placement control law is given as follow

(1) $u(t)=-Kx(t)+\delta_e.N$

where, K is the state feedback gain matrix

Controlling the pole placement provides the choice for designers to relocate every pole of the closed loop system at predefined desired positions. Thus, the state equation of the system is represented in the following manner:

(2) $\dot{x}(t)=(A-BK)x(t)$

The state equation has described the system in a combination of controller and plant. It is a homogeneous state equation that does not have an input. This state solution can be represented as:

(3) $x(t)=e^{(A-BK)t}x(0)$

The controller law of the state feedback $u=-Kx(t)$ converges the state to zero for the random initial states. Given the poles of the closed loops, the Eigenvalues

$(A-BK)$ of each pole has negative actual parts. By determining the position of the poles, it gives the ability of making the system of the closed loops stable as well as ensuring a certain group of transient conditions.

(4) det $(SI-A+BK)$ = (s-p1), (s-p2), …, (s- pn)

Selecting Eigenvalues of closed loop systems requires to understand system properties and actuator limitations. Different pole locations specify variety of performances of the system. It is the crucial portion of controller design. Thus, by examining the system performance in simulations, it gives the possibility of selecting the proper locations of poles. The design of the controller relies greatly on the value of state feed-back gain matrix (K). Also, to achieve the desired output and reduce the steady-state error, it is crucial to use a scaling factor (N) of the feed-forward to scale down the reference input. This is due to the fact that the controller doesn't compare between the given input and the desired output only. Instead, it makes a comparison of all the states of the system, that are multiplied by the feedback gain matrix, with the reference input.

Optimization Techniques

In this work, several optimization techniques, namely genetic algorithm and artificial bee colony, are implemented for determining the best locations of closed loop poles of the system and hence producing the best performance of aircraft pitch control system.

Genetic Algorithm (GA)

Genetic algorithm is comprehensive search optimizing technique that has been designed according to natural selection mechanisms. It is consisted of three fundamental phases, these are selection, crossover and Mutation. Applying those fundamental processes results in creating new members that could be more efficient compared to the predecessors. Those procedures are repeated for several generations until an ultimately stop condition is achieved at which the obtained individuals represent an optimal solution to the issue [18, 19]. The overall genetic algorithm procedure can be described in figure 3.

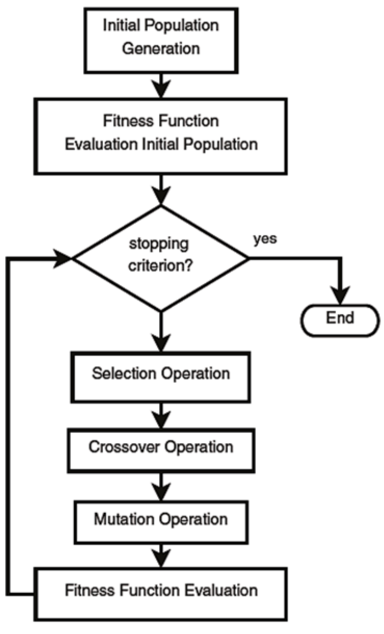


Fig. 3. Genetic algorithm flowchart.

The process of GA optimization begins with defining the structure of the chromosome. Every chromosome is constructed from three values (p1, p2, p3) that corresponding to the three closed loop poles that will be altered continuously until satisfactory behaviors are achieved. These values must be constrained to be always at the left-hand side of the s-plane. Every solution is evaluated to assess its effectiveness by measuring its quality though the fitness function to see if it meets the predefined stopping condition. The selected fitness function targets the time response characteristics of the system comprising the settling time, rise time and peak overshoot.

The GA parameters that have been chosen for optimization process of this particular system are listed in table one.

Table 1. GA parameters

Property	Value/Technique
Size of Population	50
Generations Max No.	50
Selection Probability	0.05
Selection Method	Normalized Geometric
Crossover Probability	0.2
Crossover Method	Scattering
Probability of Mutation	0.01
Mutation Method	Uniform

Artificial Bee Colony (ABC) Algorithm

This optimization technique relies on the intelligent foraging attitude of the honey bee swarm. This approach comprises three bee groups. These are the scouts, employed bees and the onlookers. The first colony half contains employed bees and the other half includes onlookers. There is only one employed bee for each food source. This leads to the fact that the size of employed bees is the same as the amount of food sources which surrounds the beehive. In this algorithm, any potential solution to the optimization task is described by the position of the food source and the amount of the food source that relates to the fitness of the corresponding solution. Therefore, The size of the employed bees is the same as the number of solutions in the population [20]. This algorithm has been mainly employed for calculating the closed loop poles of the system in a way that controlled system is capable of obtaining an efficient response of the output. Several performance criteria have been utilized in the design process including the rise time (Tr), settling time (Ts), error of the steady state (ESS) and maximum overshoot (OS%). The ABC parameters that have been chosen for this specific optimization are listed in table two.

Table 2. ABC parameters

Property	Values
size of the Colony	150
Population	50
Max. No. of Iterations	100
Dimension (No. of variable)	3
Min. Inertia Weight	0.4
Max. Inertia Weight	0.9

Simulation and Results

Pitch angle control of an aircraft system is implemented in Matlab using pole placement controller with the aid of GA and ABC optimization techniques. Initially, the parameter values chosen for running theses algorithms was selected and entered in Matlab environment. The curve of convergence for each gain (p1, p2, p3) has been plotted in figure 4 to illustrate the way that GA and ABC techniques have converged to their ultimate values.

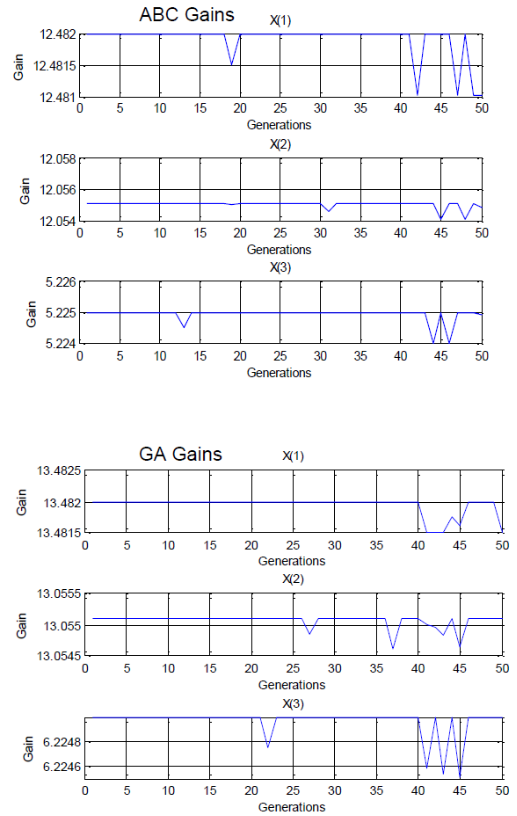


Fig. 4. ABC and GA gains output through different iterations.

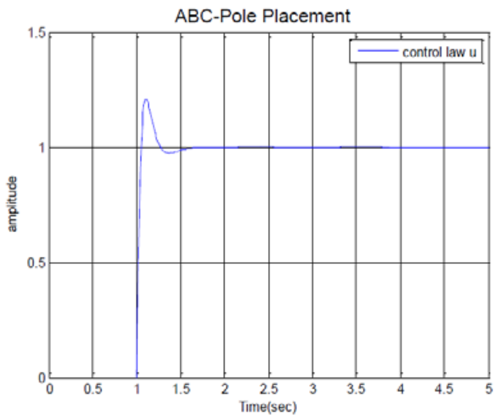
The feedback gain matrix K and the closed loop pole of the system produced through each algorithm are listed in table three. The closed loop poles are constructed as follow:

$P_1 = -X(1)$
$P_2 = -X(2) + i\,X(3)$
$P_3 = -X(2) - i\,X(3)$

Table 3. Poles and feedback gains

Parameter	GA	ABC
1st Pole (P1)	-13.4820	-12.4820
2nd Pole (P2)	$-13.0551 + i\,6.2250$	$-12.0551 + i\,5.2250$
3rd Pole (P3)	$-13.0551 - i\,6.2250$	$-12.0551 - i\,5.2250$
Feedback Gain (K)	1.0e5 [0.0000 0.1294 1.4546]	1.0e5 [0.0000 0.1216 1.1114]

The control law responses of the ABC and GA pole placement controllers are illustrated in figure 5.



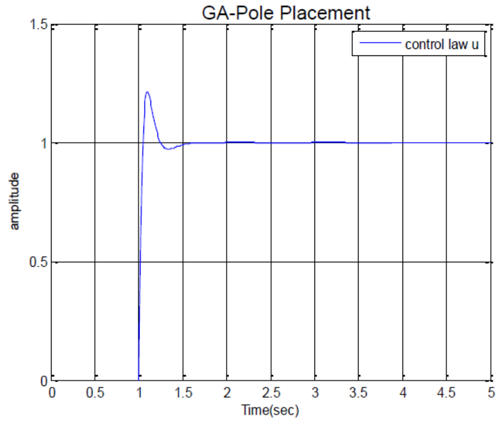


Fig. 5. Control law of ABC and GA Pole Placement controller.

The pitch angle response of ABC based Pole Placement and GA optimized Pole Placement controllers are shown in figures 6 and 7 respectively.

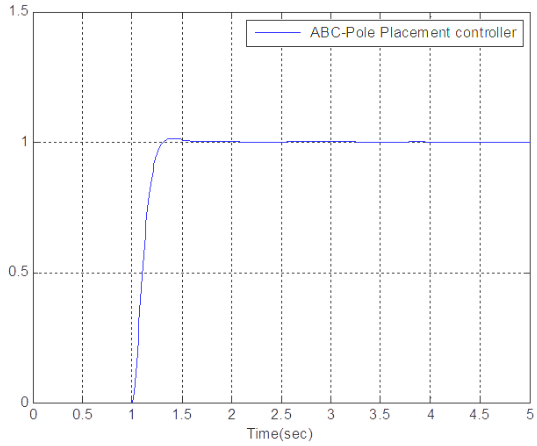


Fig.6. Pitch control response of ABC-pole placement controller

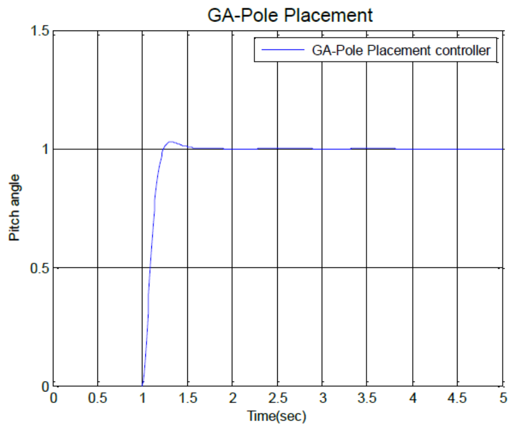


Fig. 7. Pitch control response of GA-pole placement controller

Table 4. Time response characteristics

Parameter	ABC-Pole Placement	GA-Pole Placement
Settling Time	0.2760	0.3989
Rise Time	0.1791	0.1469
Overshoot %	1.2957	2.7877
Steady State Error	0	0

Table 4 reveals performance comparison between ABC-Pole Placement and GA-Pole Placement controllers at a nominal step input. Both controllers produce a satisfactory result in term of startup transient response and steady state error. The GA based controller was able to obtain faster transient response than ABC-Pole Placement with little more overshoot during startup. However, GA-Pole Placement required a longer time to settle to its final value.

Conclusion

In the presented study, A pole placement controller has been designed and implemented to regulate the pitch angle of aircraft system. Initially, a mathematical model of an aircraft pitch system has been derived and formed in state space representation. Then, GA and ABC have been proposed to produce the best gain for the feedback matrix that determines the best location for the closed loop poles of the system. A comparative analysis of the time response characteristics between ABC based pole placement and GA-pole placement has been carried out to evaluate the performance of the designed controllers. Simulation results exhibited that ABC-pole placement controller has produced more efficient performances in comparison with GA-pole placement. The ABC optimized controller was capable of obtaining faster settling time with very little overshoot during startup as well as more stable steady-state response.

***Authors**: Abdulla I. Abdulla, Department of Systems and Control Engineering, College of Electronics Engineering, Ninevah University, Iraq, E-mail:: abdullah.abdullah@uoninevah.edu.iq ; Mohammed Almaged, Department of Systems and Control Engineering, College of Electronics Engineering, Ninevah University, Iraq, E-mail: mohammed.younus@uoninevah.edu.iq ; Salam Ibrahim khather, Department of Systems and Control Engineering, College of Electronics Engineering, Ninevah University, Iraq, E-mail: salam.khather@uoninevah.edu.iq*

REFERENCES

[1] P. B. Kumar and P. Sujatha, "QFT Robust Controller Design for Aircraft Pitch Control," International Journal of Engineering and Management Research (IJEMR), vol. 7, no. 3, pp. 399-405, 2017.
[2] M. A. Usta, Ö. Akyazi, and A. S. Akpinar, "Aircraft roll control system using LQR and fuzzy logic controller," in 2011 International Symposium on Innovations in Intelligent Systems and Applications, 2011: IEEE, pp. 223-227.
[3] L. R. Ribeiro and N. M. F. Oliveira, "UAV autopilot controllers test platform using Matlab/Simulink and X-Plane," in 2010 IEEE Frontiers in Education Conference (FIE), 2010: IEEE, pp. S2H-1-S2H-6.
[4] N. Wahid and M. F. a. Rahmat, "Pitch control system using LQR and Fuzzy Logic Controller," in 2010 IEEE Symposium on Industrial Electronics and Applications (ISIEA), 2010: IEEE, pp. 389-394.
[5] P. Boskoski, B. Mileva, and S. Deskoski, "Auto landing using fuzzy logic," in 6th International PhD Workshop on Systems and Control, 2005.
[6] D. Choe, Y. Lee, and S. Cho, "Nonlinear Pitch Autopilot Design with Local Lines Linear System Analysis," in International Conference on Automatic Control and Systems Engineering, 2005.
[7] N. Hasan, "Design and analysis of pole-placement controller for interconnected power systems," Int J Emerg Technol Adv Eng, vol. 2, no. 8, pp. 212-217, 2012.
[8] S. Eshtehardiha, A. Kiyoumarsi, and M. Ataei, "Optimizing LQR and pole placement to control buck converter by genetic algorithm," in 2007 International Conference on Control, Automation and Systems, 2007: IEEE, pp. 2195-2200.
[9] Y. Lan and M. Fei, "Design of state-feedback controller by pole placement for a coupled set of inverted pendulums," in IEEE 2011 10th International Conference on Electronic Measurement & Instruments, 2011, vol. 3: IEEE, pp. 69-73.
[10] Q. Zhu and L. Guo, "A pole placement controller for non-linear dynamic plants," Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, vol. 216, no. 6, pp. 467-476, 2002.
[11] S. Datta, D. Chakraborty, and B. Chaudhuri, "Partial pole placement with controller optimization," IEEE Transactions on Automatic Control, vol. 57, no. 4, pp. 1051-1056, 2012.
[12] J. Ohri, "GA tuned LQR and PID controller for aircraft pitch control," in 2014 IEEE 6th India International Conference on Power Electronics (IICPE), 2014: IEEE, pp. 1-6.
[13] L. Ding, H. Wu, and Y. Yao, "Chaotic artificial bee colony algorithm for system identification of a small-scale unmanned helicopter," International Journal of Aerospace Engineering, vol. 2015, 2015.
[14] D. Karaboga and B. Basturk, "On the performance of artificial bee colony (ABC) algorithm," Applied soft computing, vol. 8, no. 1, pp. 687-697, 2008.
[15] D. Karaboga and B. Akay, "A comparative study of artificial bee colony algorithm," Applied mathematics and computation, vol. 214, no. 1, pp. 108-132, 2009.
[16] L. Chrif and Z. M. Kadda, "Aircraft control system using LQG and LQR controller with optimal estimation-Kalman filter design," Procedia Engineering, vol. 80, pp. 245-257, 2014.
[17] N. Mariun, S. A. Zulkifli, H. Hizam, and N. Wahab, "Design and Simulation of Pole Placement Controller for D–STATCOM in Power Quality Problems Mitigation," WSEAS Transactions on Systems, vol. 4, no. 8, pp. 1298-1305, 2005.
[18] S. I. Khather, M. Almaged, and A. I. Abdullah, "Fractional order based on genetic algorithm PID controller for controlling the speed of DC motors," International Journal of Engineering & Technology, vol. 7, no. 4, pp. 5386-5392, 2018.
[19] M. Jaiswal and M. Phadnis, "Speed control of DC motor using genetic algorithm based PID controller," International Journal of Advanced Research in Computer Science and Software Engineering, vol. 3, no. 7, 2013.
[20] D. Karaboga and B. Basturk, "Artificial bee colony (ABC) optimization algorithm for solving constrained optimization problems," in International fuzzy systems association world congress, 2007: Springer, pp. 789-798.