IJRCS

International Journal of Robotics and Control Systems
Vol. 4, No. 2, 2024, pp. 746-757
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

ASCEE

Aircraft Pitch Control via Filtered Proportional-Integral-Derivative Controller Design Using Sinh Cosh Optimizer

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ARTICLE INFO

Article history
Received April 05, 2024
Revised May 17, 2024
Accepted May 22, 2024

Keywords
Pitch Control of Aircrafts;
Filtered PID Controller;
Sinh Cosh Optimizer;
Metaheuristics Algorithms

ABSTRACT

An innovative approach to controlling aircraft pitch is shown in this research. This approach is accomplished by adopting a proportional-integral-derivative with filter (PID-F) mechanism. A novel metaheuristic approach that we propose is called the sinh cosh optimizer (SCHO), and it is intended to further optimize the settings of the PID-F controller that is used in the aircraft pitch control (APC) configuration. An in-depth comparison and contrast of the recommended method is carried out, and statistical and time domain assessments are utilized in order to ascertain the success of the method. When it comes to managing the APC system, the SCHO-based PID-F controller delivers superior performance compared to other modern and efficient PID controllers (salp swarm based PID, Harris hawks optimization based PID, grasshopper algorithm based PID, atom search optimization based PID, sine cosine algorithm based PID, and Henry gas solubility optimization based PID) that have been published in the literature. When compared to alternative approaches of regulating the APC system, the findings demonstrate that the way that was presented is among the most successful as better statistical (minimum of 0.0033, maximum of 0.0034, average of 0.0034 and standard deviation of 5.1151E−05) and transient response (overshoot of 0%, rise time of 0.0141 s, settling time of 0.0230 s, peak time of 0.0333 s and steady-state error of 0 %) values have been achieved.

1. Introduction

Ensuring flight safety has become increasingly imperative with the surge in both air travel frequency and passenger numbers. A pivotal aspect of achieving this safety is the implementation of an efficient flight control system. The primary goal of an aircraft's flight control system is to facilitate safe and economically viable operations, ensuring mission integrity even in unforeseen circumstances. The intricate three-dimensional maneuvering of an aircraft is accomplished through control surfaces like ailerons, rudders, and elevators, which govern motions along the roll, pitch, and yaw axes [1]. Elevators situated at the aircraft's tail are instrumental in controlling its orientation by manipulating pitch and attacking angles [2].

Aircraft pitch angle control is a fundamental aspect of flight dynamics that significantly affects an aircraft's stability and performance. Over the past decade, considerable advancements have been made in developing and optimizing controllers for pitch angle regulation. Because of the non-linear and unexpected dynamics of flight, it is challenging to build flight control systems that are successful [3]. It is possible that standard controllers will not be able to reach the required level of stability and performance because of the non-linear and unpredictable character of flight dynamics. As a consequence of this, researchers have developed many alternative intelligent controllers for aircraft pitch control (APC) systems.

Classical control techniques such as proportional-integral-derivative (PID) controllers have long been the cornerstone of aircraft pitch control due to their straightforward implementation and effectiveness in a range of conditions. Studies like that by Sudha et al. [4] have shown that optimizing PID parameters using traditional methods like the Ziegler-Nichols tuning can significantly enhance the transient response and reduce the steady-state error in pitch control systems. This approach, while effective, often requires fine-tuning to address the nonlinearities inherent in aircraft dynamics.

To address the limitations of classical controllers, adaptive and robust control methods have gained prominence. Model reference adaptive control (MRAC) is one such method that has demonstrated considerable promise [5]-[10]. The study in [11] highlighted the superiority of MRAC in adapting to varying flight conditions, providing improved performance over traditional PID controllers. Similarly, robust control techniques like H∞ control, which aim to minimize the worst-case gain from disturbances to the output, have proven effective [12]-[17]. The benefits of H∞ control was showcased in maintaining pitch stability even under turbulent conditions, underscoring the robustness of this approach.

The integration of intelligent algorithms and metaheuristic optimization techniques has marked a significant shift in the landscape of aircraft pitch control. These methods are particularly effective in optimizing controller parameters and managing the complexities of nonlinear control problems. Genetic algorithms (GAs) have been extensively used for this purpose [18]-[20] . For instance, the study in [21] utilized GAs to optimize PID controller parameters, leading to substantial improvements in settling time and overshoot, thus demonstrating the effectiveness of GAs in global search and optimization tasks.

Particle swarm optimization (PSO) has also emerged as a powerful metaheuristic technique [22]-[25]. The study in [26] applied PSO to optimize an Adaptive Neuro-Fuzzy Inference System (ANFIS) for pitch control. This study highlights the potential of PSO-optimized ANFIS controllers in achieving improved control performance in complex systems, making it a promising approach for aircraft pitch angle control. The success of this method in the quadrotor application suggests its applicability to other nonlinear control problems in aerospace engineering, providing a robust and efficient solution for enhancing stability and performance.

Differential Evolution (DE) is another metaheuristic algorithm that has been explored for optimizing aircraft pitch controllers [27], [28]. The study in [29] demonstrated the efficacy of DE in optimizing the parameters of a linear quadratic regulator (LQR), resulting in superior pitch control performance. This approach underscores the versatility and efficiency of DE in addressing complex optimization problems. Hybrid approaches that combine classical control methods with metaheuristic algorithms have also shown significant promise in recent research [30], [31].

As discussed above, aircraft pitch angle regulation has made use of a number of metaheuristic algorithms. Further examples can also be found in [32]-[35]. This paper contributes to the existing literature by focusing on pitch angle control using the innovative sinh cosh optimizer (SCHO) [36]. SCHO utilizes hyperbolic trigonometric functions and incorporates exploration, exploitation, bounded search, and switching mechanisms for optimization tasks [37]. In terms of controller, a PID controller with a filter mechanism (PID-F) [38] is adopted to effectively control the aircraft pitch angle. The accurate application of the kick effect can be achieved by including a filter coefficient into the derivative gain. The effectiveness of the aircraft pitch control system is significantly improved by the proposed approach.

Results from the suggested PID-F controller were contrasted with those from different optimization algorithm-based methods documented in the literature [32], [33] in order to evaluate the efficacy of the suggested method. Comparative results indicate an improvement in aircraft pitch control system performance with the PID-F controller tuned by the proposed SCHO method as statistically minimum of 0.0033, maximum of 0.0034, average of 0.0034 and standard deviation of 5.1151E−05 are achieved. This is further supported by the transient response as an overshoot of 0%, rise time of 0.0141 s, settling time of 0.0230 s, peak time of 0.0333 s and steady-state error of 0 % are obtained via the proposed approach. These results make the proposed more advanced compared to reported approaches of salp swarm based PID controller, Harris hawks optimization based PID controller, grasshopper algorithm based PID controller, atom search optimization based PID controller, sine cosine algorithm based PID controller, and Henry gas solubility optimization based PID controller.

2. SCHO Method

Using hyperbolic trigonometric functions, especially sinh and cosh, the sinh cosh optimizer (SCHO) is a novel metaheuristic algorithm [36]. The four main parts of this algorithm are as follows: bounded search, exploration, exploitation, and switching mechanisms [37]. A set of potential solutions is initially generated at random by SCHO, as in (1), just like other metaheuristic algorithms.

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,j} & x_{1,dim-1} & x_{1,dim} \\ x_{2,1} & \cdots & x_{2,j} & \cdots & x_{2,dim} \\ \cdots & \cdots & x_{i,j} & \cdots & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{N-1,1} & \cdots & x_{N-1,j} & \cdots & x_{N-1,dim} \\ x_{N,1} & \cdots & x_{N,j} & x_{N,dim-1} & x_{N,dim} \end{bmatrix} \tag{1}$$

This equation defines the variables as follows: $x_{i,j}$ indicates the j^{th} coordinate of the i^{th} solution among a total of N potential solutions. The parameter N represents the quantity of candidate solutions, while dim signifies the dimensionality of the problem. The set X comprises randomly generated candidate solutions, computed as $X = rand(N, dim) \times (ub - lb) + lb$. Here, $rand$ denotes a random number falling within the range [0,1], and ub and lb stand for the upper and lower bounds, respectively.

The two steps that make up SCHO's exploration phase are defined by $T = floor(t_{Max}/ct)$, where ct is the switching coefficient (set to 3.6) and t_{Max} is the maximum iteration value. The first exploration phase is defined as:

$$X_{(i,j)}^{t+1} = \begin{cases} X_{(best)}^{(j)} + r_1 \times W_1 \times X_{(i,j)}^{t}, r_2 > 0.5 \\ X_{(best)}^{(j)} - r_1 \times W_1 \times X_{(i,j)}^{t}, r_2 < 0.5 \end{cases} \tag{2}$$

where $X_{(i,j)}^{t+1}$ and $X_{(i,j)}^{t}$ refer respectively to the j^{th} coordinate of the i^{th} solution in the next and current iterations. Additionally, $X_{(best)}^{(j)}$ denotes the j^{th} coordinate of the best solution attained thus far. The variables r_1 and r_2 represent random numbers within the range [0,1]. The coefficient W_1 in the initial exploration phase is determined by $W_1 = r_3 \times \alpha_1 \times (cosh\, r_4 + 0.388 \times sinh\, r_4 - 1)$. Here, r_3 and r_4 are random numbers within [0,1] and $\alpha_1 = 3 \times (-1.3 \times (t/t_{Max}) + 0.45)$. In the second exploration phase, the position update rule is given by:

$$X_{(i,j)}^{t+1} = \begin{cases} X_{(i,j)}^{t} + \left|0.003 \times W_2 \times X_{best}^{(j)} - X_{(i,j)}^{t}\right|, r_5 > 0.5 \\ X_{(i,j)}^{t} - \left|0.003 \times W_2 \times X_{best}^{(j)} - X_{(i,j)}^{t}\right|, r_5 < 0.5 \end{cases} \tag{3}$$

where $W_2 = r_6 \times \alpha_2$, r_5 and r_6 are random numbers within [0,1], and $\alpha_2 = 2 \times (-(t/t_{Max}) + 0.5)$.

There are two steps to the exploitation phase, just as there are to the exploration phase. Use of (4) occurs during the initial stage of exploitation:

$$X_{(i,j)}^{t+1} = \begin{cases} X_{best}^{(j)} + r_7 \times W_3 \times X_{(i,j)}^{t}, r_8 > 0.5 \\ X_{best}^{(j)} - r_7 \times W_3 \times X_{(i,j)}^{t}, r_8 < 0.5 \end{cases} \tag{4}$$

where r_7 and r_8 are random numbers within [0,1], and $W_3 = r_9 \times \alpha_1 \times (\cosh r_{10} + 0.388 \times \sinh r_{10})$, with r_9 and r_{10} being random numbers within [0,1]. In the second exploitation phase, deep exploitation around the optimal solution is performed using:

$$X_{(i,j)}^{t+1} = X_{(i,j)}^{t} + r_{11} \times \frac{\sinh r_{12}}{\cosh r_{12}} \left| W_2 \times X_{best}^{(j)} - X_{(i,j)}^{t} \right| \tag{5}$$

where r_{11} and r_{12} are random numbers within [0,1]. SCHO also employs a bounded search strategy, given by (6).

$$BS_{k+1} = BS_k + floor[(t_{Max} - BS_k)/4.6] \tag{6}$$

In this strategy, k represents a positive integer beginning from 1. The terms BS_{k+1} and BS_k denote respectively the number of iterations commencing the subsequent and ongoing bounded search strategy.

In the end, SCHO incorporates a switching mechanism to go from exploration to exploitation. The description of the switching mechanism is given in (7):

$$A = \left(10 - 9 \times (t/t_{Max})^{\frac{\cosh(t/t_{Max})}{\sinh(t/t_{Max})}}\right) \times r_{13} \tag{7}$$

where r_{13} represents random number within [0,1]. For $A > 1$, SCHO performs exploration, and for $A < 1$, exploitation is executed. A detailed flowchart of the SCHO method is presented in Fig. 1.

3. Proposed PID-F Controlled APC System

3.1. PID-F Controller

One common feedback control system used in engineering and industry is the PID controller. Its job is to maintain a setpoint by constantly modifying a control variable according to the difference between the setpoint and the real process variable. This control mechanism incorporates three essential components, namely proportional (K_P), integral (K_I), and derivative (K_D), as articulated in (8) [39]-[41].

$$C_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \tag{8}$$

This research proposes a new method for the APC system by combining a PID controller with a filtering mechanism (PID-F) as opposed to the traditional PID controller. Incorporating this novel control approach into the APC system greatly improves its performance. Equation in (9) is the definition of the PID-F controller's transfer function, where N is the low-pass filter gain [38], [42].

$$C_{PID-F}(s) = K_P + \frac{K_I}{s} + K_D \frac{Ns}{s + N} \tag{9}$$

The PID-F controller has a special benefit since it successfully reduces the kick effect by incorporating a filter coefficient into the derivative gain. As a result, this improvement improves the APC system's immunity to noise. Fig. 2 depicts the block diagram for the PID-F controller.

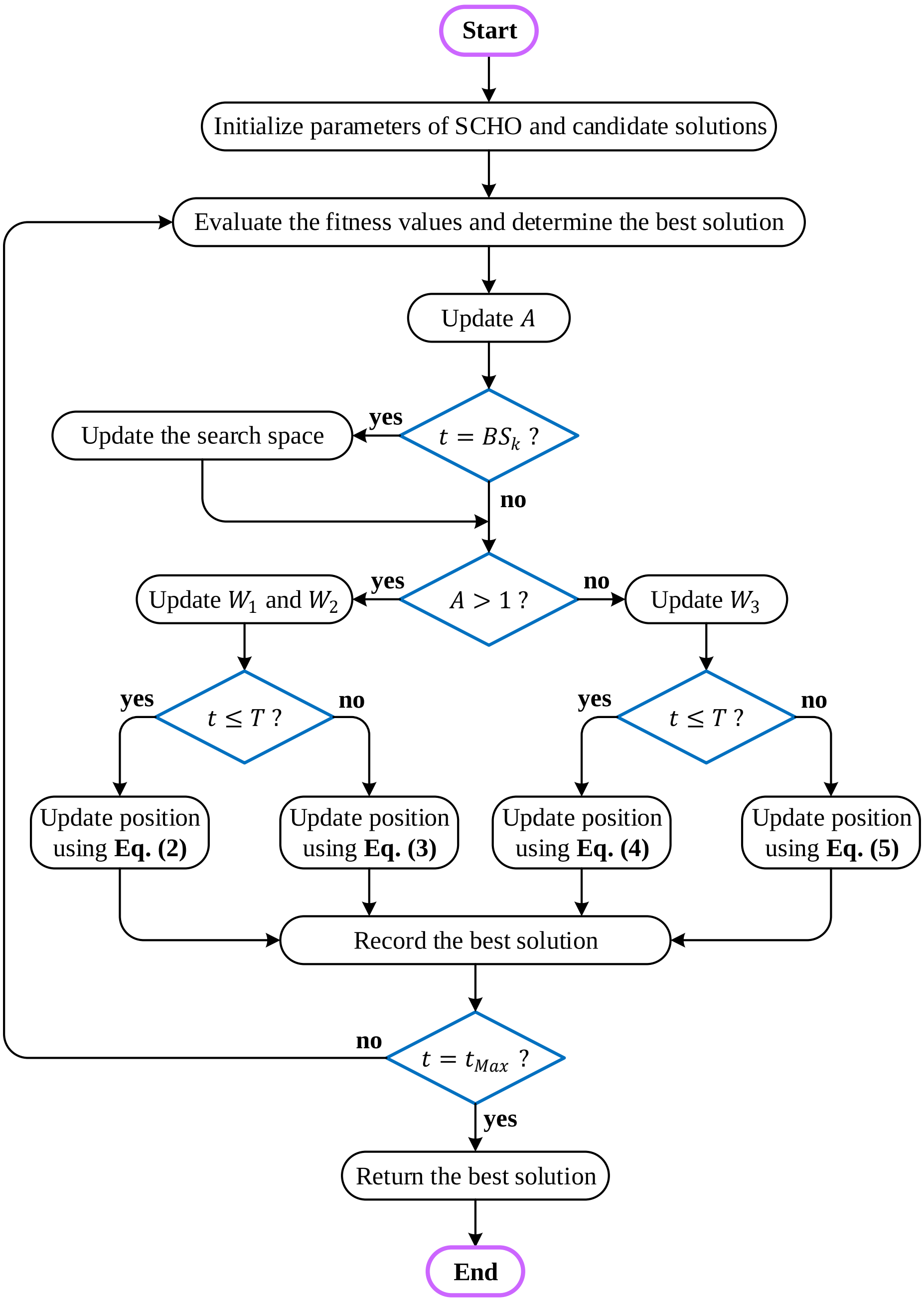

Fig. 1. Flowchart of SCHO

3.2. Objective Function

This paper uses a systematic technique to formulate the APC system in terms of a minimization issue that can be solved using optimization algorithms. The system is characterized as a minimization issue by describing the parameters of the PID-F controller, denoted as $\vec{X} = [x_1, x_2, x_3, x_4] = [K_P, K_I, K_D, N]$. Subsequently, the optimization process is facilitated through the utilization of an objective function, referred to as ZLG [43], [44], serving as a time-domain metrics-based minimization tool. The ZLG cost function, [43], [45]-[47], is expressed in (10).

$$ZLG = (1 - e^{-\mu}) \times (m_p + e_{ss}) + e^{-\mu} \times (t_{set} - t_{rise}) \tag{10}$$

In here, μ denotes a balancing factor set to 1, e_{ss} represents the steady-state error, m_p signifies the overshoot, t_{set} denotes the settling time, and t_{rise} corresponds to the rise time [48]-[50]. To enhance the PID-F controller parameters and attain the desired system performance, ZLG serves as the objective function.

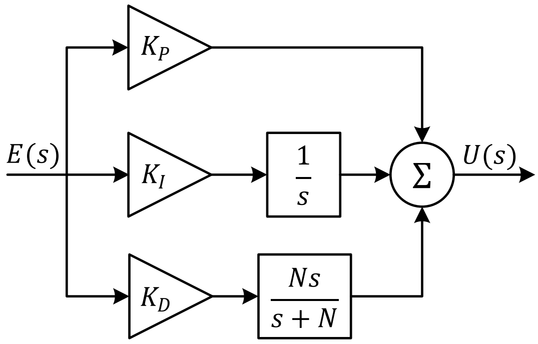

Fig. 2. Block diagram of PID-F controller

3.3. Application of SCHO to APC System

Fig. 3 shows the details of how the SCHO is applied to the APC system. One step of the method is determining the objective function using the pitch angle value. The system's performance can be measured using this objective function. Following this, the SCHO method is used to dynamically adjust the PID-F controller's parameters. The primary goal is to minimize the objective function value through iterative adjustments to the PID-F controller parameters. In simpler terms, the SCHO method leverages information from the pitch angle to assess how well the APC system is performing. It then refines the PID-F controller parameters in a systematic manner, with the aim of continuously improving the system's performance and achieving the lowest possible value for the objective function over multiple iterations.

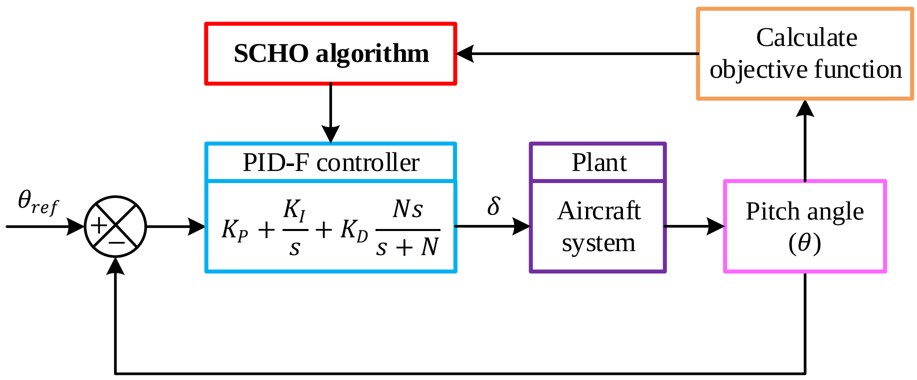

Fig. 3. Block diagram of proposed novel design method for APC system

4. Simulation Results and Discussion

4.1. Results for the Proposed Method

In the simulation study, the proposed method was evaluated with a population size of 30 and a total of 50 iterations conducted over 15 independent runs. The SCHO was applied to determine the optimal PID-F controller parameters. After 15 runs, the best parameters obtained were as follows: $K_P = 17.1800$, $K_I = 98.5307$, $K_D = 98.4932$ and $N = 353.7853$. Using these optimized parameters, the transfer function (given in (11)) representing the system dynamics was derived, taking into account the structural configuration of the system, illustrated in Fig. 4.

$$T_{SCHO}(s) = \frac{40127s^3 + 13295s^2 + 41219s + 6185}{s^5 + 354.5s^4 + 40390s^3 + 13621s^2 + 41219s + 6185} \tag{11}$$

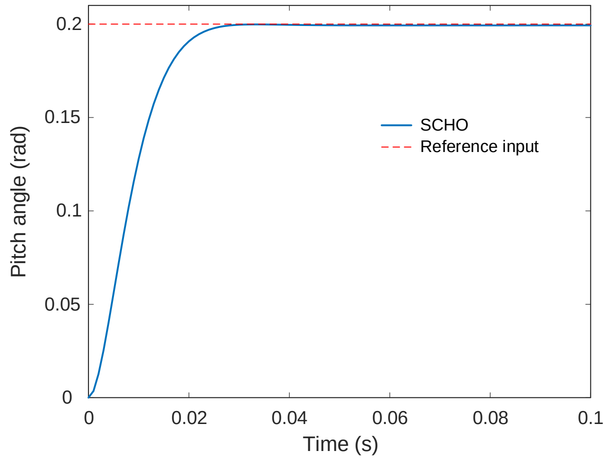

Fig. 4. Step response of SCHO-based PID-F controlled APC system

4.2. Compared Algorithms

In order to conduct a comprehensive comparative analysis, various optimization algorithms previously documented in the literature were considered. Specifically, the following methodologies were included for evaluation: salp swarm based PID (SSA/PID) [32], Harris hawks optimization based PID (HHO/PID) [32], grasshopper algorithm based PID (GOA/PID) [33], atom search optimization based PID (ASO/PID) [32], sine cosine algorithm based PID (SCA/PID) [33], and Henry gas solubility optimization based PID (HGSO/PID) [33] were used in this study. The controller parameters obtained through the aforementioned approaches have been systematically compiled and are presented in Table 1 for clarity and comparative purposes.

Table 1. Obtained parameters via reported approaches

Algorithm	K_P	K_I	K_D
HHO	55.2698	51.4031	90.9434
ASO	17.3672	24.2791	84.5323
SSA	84.6747	68.0177	76.8185
SCA	70.8938	64.8932	72.4551
GOA	63.8156	21.5434	77.6758
HGSO	69.7726	3.6054	95.1465

4.3. Statistical Validation of SCHO

To assess the performance of the SCHO in optimizing the ZLG objective function, statistical metrics were employed. The results of these metrics are summarized in Table 2. The statistical metrics include the minimum, maximum, average, and standard deviation (Std. Dev.) of the ZLG objective function values obtained from each algorithm. Additionally, the algorithms are ranked based on their performance in minimizing the objective function. From the results, it is evident that the SCHO achieves the lowest average ZLG objective function value compared to other algorithms, indicating superior performance in optimizing the APC system. Moreover, SCHO also exhibits the lowest standard deviation, suggesting consistency in its optimization results. Therefore, based on these statistical validations, it can be concluded that SCHO is a robust and effective optimization algorithm for tuning the PID-F controller parameters in the context of the APC system.

4.4. Transient Response Analysis

The transient response performance of various optimization algorithms applied to the APC system is systematically evaluated, and the outcomes are summarized in Table 3. The presented table outlines key transient response parameters, namely overshoot, rise time, settling time, peak time, and steady-state error, for each algorithm. Observing the results, the SCHO demonstrates an optimal transient response with zero overshoot and minimal rise time and settling time. In contrast, other algorithms exhibit varying degrees of overshoot and time-related metrics. Notably, the SCHO algorithm showcases a superior performance in achieving a fast and stable response with minimal oscillations and settling time. This behavior can also be observed from the illustrations given in Fig. 5 and Fig. 6. These findings underscore the efficacy of the SCHO algorithm in enhancing the transient response characteristics of the APC system.

Table 2. Statistical metric results of ZLG objective function

Algorithm	Minimum	Maximum	Average	Std. Dev.	Rank
SCHO	0.0033	0.0034	0.0034	5.1151E−05	1
HHO	0.0060	0.0073	0.0065	3.5298E−04	3
ASO	0.0071	0.0083	0.0077	3.4295E−04	4
SSA	0.0092	0.0100	0.0096	2.4566E−04	7
SCA	0.0091	0.0098	0.0094	2.3515E−04	6
GOA	0.0074	0.0096	0.0081	6.3267E−04	5
HGSO	0.0056	0.0063	0.0059	2.0814E−04	2

Table 3. Transient response performance of different approaches

Algorithm	Overshoot (%)	Rise time (s)	Settling time (s)	Peak time (s)	Steady-state error (%)
SCHO	0	0.0141	0.0230	0.0333	0
HHO	0	0.0210	0.0373	0.0700	0
ASO	0	0.0229	0.0423	0.1023	0
SSA	0.4511	0.0244	0.0417	0.0833	0
SCA	0.3464	0.0260	0.0447	0.0827	0
GOA	0.1158	0.0244	0.0426	0.0770	0
HGSO	0	0.0200	0.0352	0.0627	0

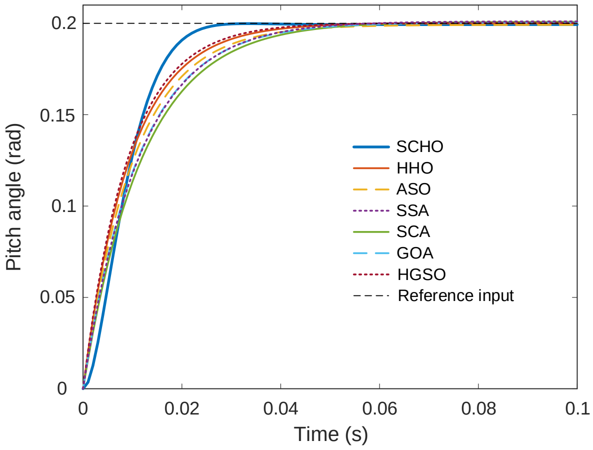

Fig. 5. Comparative step responses

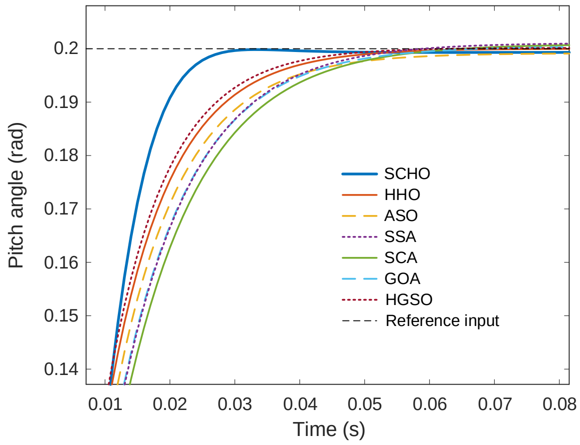

Fig. 6. Enlarged view of Fig. 5

5. Conclusion

The field of aircraft pitch angle control has seen a substantial evolution towards integrating advanced adaptive techniques and metaheuristic optimization methods over the past decade. These approaches provide robust solutions to the challenges posed by nonlinearities and uncertainties in aircraft dynamics. This study advances the field of APC by introducing a pioneering approach through the implementation of the SCHO as a metaheuristic algorithm to optimize PID-F controller parameters. The evaluation of the proposed approach involved rigorous comparative analyses, encompassing both statistical and time domain assessments. To establish a benchmark, recent and effective metaheuristic algorithms based PID controllers from the literature were included in the comparisons. The results unequivocally confirm the superior performance of the SCHO-based PID-F controller in governing the APC system when compared to alternative mechanisms. The demonstrated effectiveness of the proposed approach underscores its potential applicability and impact in the realm of APC systems. The successful integration of the PID-F mechanism with the SCHO algorithm showcases promising prospects for enhancing aircraft flight control precision, particularly in dynamic and uncertain environments. Future research is likely to delve deeper into hybrid and intelligent systems, potentially incorporating machine learning techniques to enhance predictive capabilities and adaptive performance. The continuous development in this area promises to further improve the stability and performance of aircraft pitch control systems.

Author Contribution: All authors contributed equally. The final paper was checked and approved by all authors.

Funding: There was no financial support received for this work.

Conflicts of Interest: None of the authors present any conflicts of interest.

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