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PID Controller Tuning by Bacterial Foraging - PSO Algorithm for Pitch Control of Aircraft System

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Abstract: The combination of nonlinear dynamics, modeling uncertainties and parameter variation in characterizing an aircraft and operating environment are one major problem. The control system of the aircraft can be divided into two parts which are longitudinal and lateral control. Pitch control is a longitudinal problem which is utilized to design autopilot. In this paper, we proposed Bacterial Foraging Optimization Algorithm (BFOA) for tuning the PID controller. To achieve better results, for such critical control scheme. These controllers are compared with conventional order controls. These design schemes show a practical and systematic way of the controller design for the considered class of fractional order system. Bacterial Foraging Optimization Algorithm (BFOA) has lately emerged as a very potent technique for real parameter optimization.

Keywords: Pitch control; Bacterial Foraging Optimization; PSO; PID; Integral Square Error.

1. INTRODUCTION

Modern aircraft include a mixture of an automatic control system that assists the flight team in direction-finding, flight management and augmenting the stability characteristic of the airplane. In this condition, an autopilot is designed that control the pitch of aircraft that can be used by the flight team to lessen their workload during cruising and assist them to set down their aircraft during unfavorable weather conditions in the real situation[1]. The autopilot is an element within the trajectory control scheme. It is a pilot relief mechanism that helps in maintaining an attitude, heading, altitude or flying to navigation or landing references[2]. Designing an autopilot requires fundamental of control theory and knowledge of stability derivatives at different altitudes and Mach numbers for a given airplane[3]. A lot of studies has been performed in the past to control the pitch of an aircraft for the use of flying stability and even so this research still remains an unresolved issue in the present and future works[4-6].

As a consequence of wide investigation to formulate methods of choosing optimum controller setting for the PID controller, Ziegler and Nichols [7,8] showed how they could be estimated using open and closed loop tests on the plants. The method is referred to as ZN rules. The ZN setting usually experiences excessive overshoot of the plant response. With the ease of computation, mathematical optimization methods become significant in the devising formula for PI, PD and PID controller parameter tuning[9]. The squared error integral criteria are the most common for such optimization[10].

Several optimization techniques using the swarming principle have been adopted to solve a variety of engineering problems in the past decade. The work is inspired by the way these insects communicate. Swarming strategies in bird flocking and fish schooling are used in the Particle Swarm Optimization (PSO) introduced by Eberhart and Kennedy[11]. A relatively newer evolutionary computation algorithm, called Bacterial Foraging scheme has been proposed and introduced recently by K.M. Passino[12].

In this paper, the use of both PSO and (E. coli) based optimization for PID parameter tuning is investigated. A new algorithm bacterial foraging oriented by particle swarm optimization (BF-PSO) is proposed that combine the above-mentioned optimization algorithms.

2. MODELING OF A PITCH CONTROL

Effective control can be achieved by proper modeling mode even after using different inputs to the aircraft. The equation for governing the motion of an aircraft can be split into two groups to melt off the complexity of the psychoanalysis. These two groups are longitudinal and lateral equations. Figure 1 represents the pitch control system. In this figure X_b, Y_b and Z_b represent the aerodynamic force components as well as θ, Φ and δe represent the elevator deflection angle and the orientation of the aircraft pitch angle in the earth axis system[13].

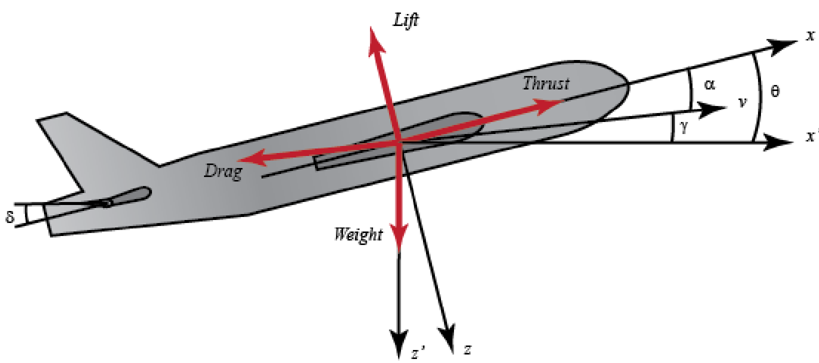

Figure 1: Air Pitch Control System

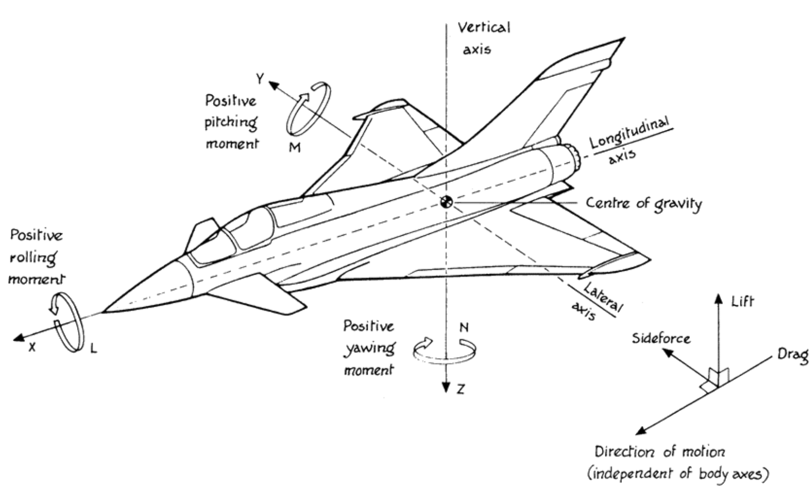

Figure 2: Different forces, moments and velocity components of the aircraft system

Figure 2 shows the forces, moments and velocity components of the aircraft system. The roll, pitch and yaw axis of the representation as L, M, and N-term. Also the term p, q, and r represent the angular rates about roll, pitch and yaw axis. The term u, v and w represent the velocity components of roll, pitch and yaw axis and α and β are represents the angle of attack and sideslip. The data from General Aviation Aeroplane[14] is used in the system for analysis and modeling.

For the thrust and drag are cancel out and lift and weight balance out each other, the aircraft is assumed as the steady state cruise at constant attitude and velocity as well as under any circumstance, the change in pitch angle does not change the speed of an aircraft. These two assumptions need to be considered before continuing with the modeling process[15].

Table 1
Longitudinal stability derivative parameters

Longitudinal Derivatives	*Components Dynamic Pressure and Dimensional Derivative Q = 36.81 lb/ft2, QS = 6771 lb, QS$\bar{c}$ = 38596 ft.lb. ($\bar{c}$ /2u_0) = 0.016s*		
	X-Force (S-1)	*Z-Force (S-1)*	*Pitching Moment(FT-1)*
Rolling Velocities	Xu = –0.045	Zu = –0.369	Mu = 0
Yawing Velocities	Xw = 0.036 X $\dot{w}$ = 0	Zw = –2.02 Z $\dot{w}$ = 0	Mw = –0.05 M $\dot{w}$ = –0.051
Angle Of Attack	Xα = 0 X $\dot{\alpha}$ = 0	Zα = –355.42 Z $\dot{\alpha}$ = 0	Mα = –8.8 M $\dot{\alpha}$ = –0.8976
Pitching Rate	Xq = 0	Zq = 0	Mq = –2.05
Elevator Deflection	Xδe = 0	Zδe = –28.15	Mδe = –11.874

The longitudinal stability derivatives parameters used are denoted in Table 1. Equation (1), (2) and (3) represent the dynamic equations for the aircraft pitch control.

$$\mathrm{X} - mg\mathrm{S}\theta = m(\dot{u} + q_v - r_v) \tag{1}$$

$$\mathrm{Z} + mg\mathrm{C}\theta\mathrm{C}\Phi = m(\dot{w} + p_v - q_u) \tag{2}$$

$$\mathrm{M} = \mathrm{I}_y\ \dot{q} + r_q(\mathrm{I}_x - \mathrm{I}_z) + \mathrm{I}_{xz}(p_2 - r_2) \tag{3}$$

where,

X = x directional force

m = mass of aircraft

g = gravity force

θ, Φ, δe = Orientation of aircraft in earth system & elevator deflection angle

L = aerodynamics moment components for Roll Axis

M = aerodynamics moment components for Pitch Axis

N = aerodynamics moment components for Yaw Axis

p = Angular Axis about to Roll Axis

q = Angular Axis about to Pitch Axis

r = Angular Axis about to Yaw axis

u = Velocity component for Roll Axis

v = Velocity component for Pitch Axis

w = Velocity component for Yaw Axis

α = angle of attack

β = angle of sideslip

Above Equations should be literalized using small disturbance theory. The equations are replaced by a variable or reference value plus a perturbation or disturbance,

$$u = u_0 + \Delta u \qquad p = p_0 + \Delta p \qquad \mathrm{X} = \mathrm{X}_0 + \Delta\mathrm{X}$$

$$v = v_0 + \Delta v \qquad s = s_0 + \Delta s \qquad r = r_0 + \Delta r$$

$$\mathrm{M} = \mathrm{M}_0 + \mathrm{MY} \qquad \mathrm{Z} = \mathrm{Z}_0 + \Delta\mathrm{Z} \qquad \delta = \delta_0 + \Delta\delta$$

$$w = w_0 + \Delta w$$

For convenience, the reference flight condition is assumed to be symmetrical and propulsive forces are assumed to remain constant. For that The values of $u_0 = v_0 = \mathrm{M}_0 = p_0 = s_0 = \mathrm{Z}_0 = w_0 = \mathrm{X}_0 = r_0 = \delta_0 = 0$. After the linearization the following equations are found.

$$\left(\frac{d}{dt} - \mathrm{X}_u\right)\Delta u - \mathrm{X}_u \Delta w + (g\cos\theta_0)\Delta\theta = \mathrm{X}\delta e\,\Delta\delta e \tag{4}$$

$$-\mathrm{Z}u\Delta u + \left[(1-\mathrm{Z}_w)\frac{d}{dt} - \mathrm{Z}_w\right]\Delta w\left[(u_o + \mathrm{Z}_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta = \mathrm{Z}\delta e\Delta\delta e \tag{5}$$

$$-\mathrm{M}u\Delta u - \left(\mathrm{M}_w\frac{d}{dt} + \mathrm{M}_w\right)\Delta w + \left(\frac{d^2}{dt^2} - \mathrm{M}_q\frac{d}{dt}\right)\Delta\theta = \mathrm{M}\delta e\Delta\delta e \tag{6}$$

After substituting longitudinal stability derivative parameters from table 1 to the above equations (4), (5) and (6), the following transfer function for the change in the pitch rate to the change in elevator deflection angle is shown in the following equation (7)

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-(\mathrm{M}_{\delta e} + \mathrm{M}_\alpha \mathrm{Z}_{\delta e}/u_0)s - (\mathrm{M}_\alpha \mathrm{Z}_{\delta e}/u_0 - \mathrm{M}_{\delta e}\mathrm{Z}_\alpha/u_0)}{s^2 - (\mathrm{M}_q + \mathrm{M}_\alpha + \mathrm{Z}_\alpha/u_0)s + (\mathrm{Z}_\alpha \mathrm{M}_q/u_0 - \mathrm{M}_\alpha)} \tag{7}$$

The transfer function of the change in pitch angle to the change in elevator angle can be obtained from the change in pitch rates to the change in elevator angle in the following way.

$$\Delta q = \Delta\dot{\theta} \tag{8}$$

$$\Delta q(s) = s\Delta\theta(s) \tag{9}$$

$$\frac{\Delta\theta(s)}{\Delta\delta e(s)} = \frac{1}{s}\cdot\frac{\Delta q(s)}{\Delta\theta(s)} \tag{10}$$

Thus, the transfer function of the aircraft pitch control system is represented by the following equation (11) and (12)

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}\frac{-(M_{\delta e} + M_\alpha Z_{\delta e}/u_0)s - (M_\alpha Z_{\delta e}/u_0 - M_{\delta e} Z_\alpha/u_0)}{s^2 - (M_q + M_\alpha + Z_\alpha/u_0)s + (Z_\alpha M_q/u_0 - M_\alpha)} \tag{11}$$

After evaluating all values from the Table 1, the transfer function of the aircraft pitch control is

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{11.732s + 22.3}{s^3 + 4.9376s^2 + 12.89s} \tag{12}$$

3. METHODOLOGY

In this section, two feedback control schemes are proposed and describe in detail which is PID and self-tuning fuzzy PID for control the pitch angle of an aircraft. The block diagram of analog PID control system is showed in Figure 1.

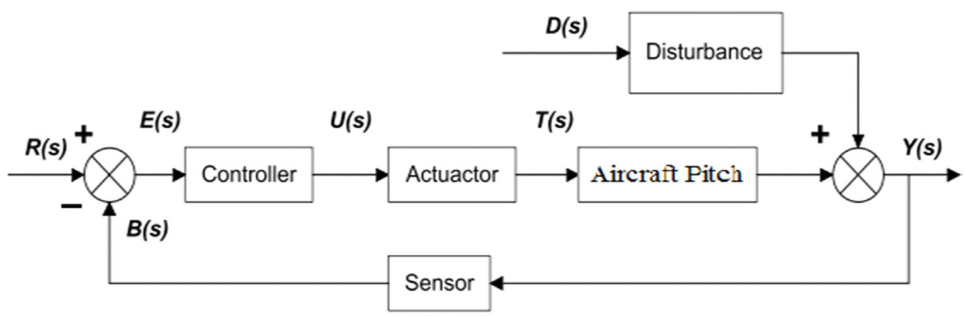

Figure 3: Control scheme of aircraft pitch system

A. PID Controller

PID Controller Proportional integral derivative controller (PID) regarded as the standard control structures of the classical control theory. PID is a common control loop feedback mechanism extensively used in industrial control systems. The performance design of the system can be improved by tuning the value of gain proportional gain (K_p), integral gain (K_i), and derivative gain (K_d). The selection of these values will cause for variation in observed response because each component has its own special purposes. The mathematical description of linear relationship between the controller output, $u(t)$ and the error, $e(t)$ is expressed

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

In this work the controller parameters of PID controller are set to $K_p = 4.15$, $K_i = 0.04$ and $K_d = 0.9$.

B. Self-tuning Bacterial Foraging based PSO Optimization Algorithm PID

Natural selection tends to eliminate animals with poor foraging strategies and favor the propagation of genes of those animals that have successful foraging strategies since they are more likely to enjoy reproductive success[16].In this foraging theory, the objective of the animal is to search for and obtain nutrients in a fashion that energy intake per unit time (E/T) is minimized[8]. A group of bacteria moves in search of food and away from noxious elements are known as Foraging. BFO algorithm draws its inspiration from this foraging behavior. Bacteria have a trend to amass to the nutrient-rich regions of activity called Chemotaxis. Its cause and behavior are characterized by the spinning flagella which acts as a Biological motor and helps bacteria to float[17].

BF-PSO algorithm combines both BFO and PSO. The objective is to make PSO ability to exchange social information and BF ability in discovering new solutions by elimination and dispersal, a unit length direction of tumble behavior is randomly generated. Random direction may conduct to delay in reaching the global result. In "BF-PSO" algorithm the unit length random direction of tumble behavior can be determined by the global best position and the best view of each bacterium. During the chemotaxis loop tumble, direction is updated by

$$\xi(j+1) = \omega \times \xi(j) + C_1 \times \text{rand}(p_{\text{best}} - p_{\text{current}}) + C_2 \times \text{rand}(g_{\text{best}} - p_{\text{current}})$$

where, pbest is the best position of each bacterium and gbest is the global best bacterium. Automatic tuning of PID can be done based on minimizing the performance index which is given as:

Algorithm to find optimal parameters using BFO for the objective function (Integral time absolute error) ITAE is described below:

$$\text{ITAE} = \int_0^{\infty} e(t)\, dt$$

Step 1: Initialize the parameters

$\boldsymbol{p}$ – length of the search space;

S – Number of bacteria in the population;

$\mathbf{N}_s$ – Swimming length after which tumbling of bacteria will be undertaken in chemotactic loop;

$\mathbf{N}_c$ – The number of iterations to be undertaken in chemotactic loop, always $N_c > N_s$;

$\mathbf{N}_{re}$ – Maximum no. of reproduction steps;

$\mathbf{N}_{ed}$ – the maximum no. of Elimination and dispersal events to be imposed over bacteria;

$\boldsymbol{p}_{ed}$ – Probability with which elimination and dispersal will continue;

θ^i – Location of the i^{th}(i = 1, 2, 3, ..., S) bacterium;

C(*i*) – Step size of the i^{th} bacterium taken in a random direction, specified by tumble.

Generate a random vector $\xi(j)$ in the range [–1 1]

C_1, C_2,: swarm confidence

ω: The inertia weight

$\theta(i, j, k)$ = Position vector of the i^{th} bacterium, in j^{th} chemotactic step and k^{th} reproduction

Step 2: Update cost function ($J(i, j, k)$) of the i^{th} bacterium, in j^{th} chemotactic step and k^{th} reproduction loop: $l = l + 1$

Step 3: Reproduction loop: $k = k + 1$

Step 4: Chemotaxis loop: $j = j + 1$

For i = 1, 2, 3, ..., S

(i) take a chemotactic step for bacterium i as follows

(ii) Compute fitness function, ITAE(i, j, k).

(iii) Let $\text{ITAE}_{\text{last}} = \text{ITAE}(i, j, k, l)$ save this value, since we may get better value via a run.

(iv) Tumble: generate the random vector $\Delta(i) \in \text{R}^n$ with each element $\Delta_m(i)$, $m = 1, 2, 3, ..., n$, a random value on $[-1 \quad 1]$.

(v) Move: Assume $\theta(i, j+1, k) = \theta(i, j, k) + \text{C}(i) \dfrac{\Delta(i)}{\sqrt{\Delta^{\text{T}}(i)\Delta(i)}}$

(vi) Calculate $\text{ITAE}(i, j+1, k)$.

(vii) Swim

Assume $m = 0$ (counter for swim length)

while $m < \text{N}s$ (if the bacteria have not climbed tolong)

(viii) Let us consider $m = m + 1$

- If $\text{ITAE}(i, j+1, k) < \text{ITAE}_{\text{last}}$ (for better doing)
- Assume $\text{ITAE}_{\text{last}} = \text{ITAE}(i, j+1, k)$ and $\theta(i, j+1, k) = \theta(i, j, k) + \text{C}(i) \dfrac{\Delta(i)}{\sqrt{\Delta^{\text{T}}(i)\Delta(i)}}$ and use $\theta(i, j+1, k)$ to compute the new ITAE.
- Elese, assume $m = \text{N}_s$

Step 5: Mutation with PSO oerator for $i = 1, 2, 3, ..., \text{S}$

- Update the $\theta_{\text{g\_best}}$ and $\text{ITAE}_{\text{best}}(i, j, k)$
- Update the position and the velocity of the d^{th} coordinate of the i^{th} bacterium according to the following rule:

$$\xi(j+1) = \omega \times \xi(j) + \text{C}_1 \times \text{rand}(p_{\text{best}} - p_{\text{current}}) + \text{C}_2 \times \text{rand}(g_{\text{best}} - p_{\text{current}})$$

$$\theta^i(j+1, k, l) = \theta^i(j, k, l) + \text{C}(i)\xi(j)$$

Step 6: Let $\text{S}_r = \text{S}/2$

The S_r bacteria with highest cost function (ITAE) values die and other half bacteria population with the best values split.

Step 7: If $k < \text{N}_{re}$, go to step 3. One has not reached the number of specified reproduction steps, so one starts the next generation in the chemotaxis loop.

4. SIMULATIONS AND TESTING

Figure 1 shows the unit step response of closed loop system in which PID controller is tuned by conventional Ziegler-Nichols method and BF-PSO based optimization method. Table 1 shows the different transient parameters of PID controller. The transient parameters considered are settling time, peak overshoot, ISE (integral square error) and ITAE (integral time absolute error).

Bacteria parameters: Number of bacteria = 20; number of chemotatic steps = 10; number of elimination and dispersal events = 2; number of reproduction steps = 4; probability of elimination and dispersal = 0.25. PSO parameters: $\text{C}_1 = \text{C}_2 = 2.0$, $\omega = 0.8$.

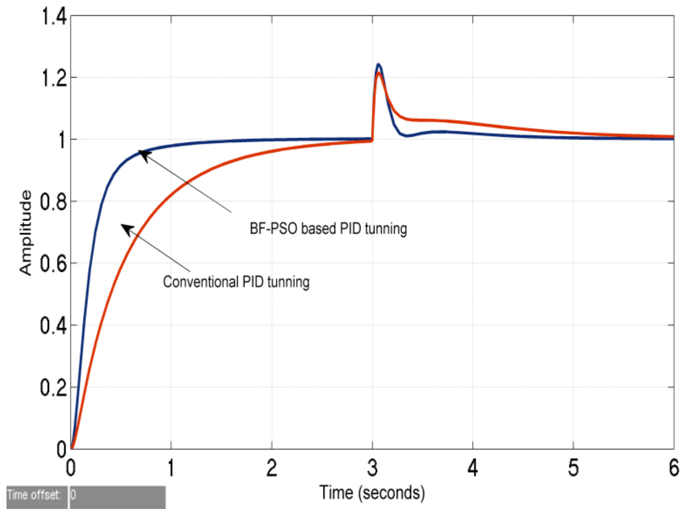

Figure 4: Step response of the closed loop system with the BF-PSO-PID controller using ITSE based fitness function and conventional PID controller

Table 1
Different transient parameters of PID and BF-PSO based PID controller

	Conventional PID Tuning $K_p = 4.15, K_i = 0.04, K_d = 0.9$	*BF-PSO based tuning* $K_p = 9.21, K_i = 0.91, K_d = 1.53$
Rise Time (Sec)	1.9195	0.5062
Settling Time (Sec)	2.3993	0.6328
Integral Square Error (ISE)	0.0797	0.0094
Integral Time Absolute Error (ITAE)	0.404	0.0323
Integral Absolute Error (IAE)	0.3421	0.2930

5. CONCLUSION

In this paper, a new BF oriented by the PSO optimization algorithm is proposed. This algorithm combines PSO and BF techniques in order to make use of PSO ability to exchange social information and BF ability in discovering a new solution by elimination and dispersal. The suggested technique is applied to the PID parameter tuning for a set of test plants. Modeling is done on an aircraft pitch control and self-tuning BF-PSOPID is proposed successfully. The proposed control schemes have been implemented within simulation environment in Matlab and Simulink. The performance of the control schemes has been evaluated in term of time domain specification.

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