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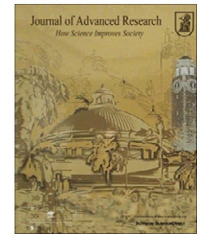

ORIGINAL ARTICLE

Design of aerospace control systems using fractional PID controller

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Abstract The goal is to control the trajectory of the flight path of six degree of freedom flying body model using fractional PID. The design of fractional PID controller for the six degree of freedom flying body is described. The parameters of fractional PID controller are optimized by particle swarm optimization (PSO) method. In the optimization process, various objective functions were considered and investigated to reflect both improved dynamics of the missile system and reduced chattering in the control signal of the controller.

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Introduction and literature review

In recent years, the requirements for the quality of automatic control increased significantly due to increased complexity of plants and sharper specifications of product. This paper will address the design of optimal variable structure controllers applied to a six degree of freedom missile model which is the solution to obtain a detailed accurate data about the missile trajectory. The paper objectives are: (a) to develop a general flexible sophisticated mathematical model of flight trajectory simulation for a hypothetical anti-tank missile, which can be used as a base line algorithm contributing for design, analysis, and development of such a system and implement this model using Simulink to facilitate the design of its control system, and (b) developing control system, by using fractional PID control techniques.

According to MacKenzie, guidance is defined as the process for guiding the path of an object toward a given point, which in general is moving [1]. Furthermore, the father of inertial navigation, Charles Stark Draper, states that “Guidance depends upon fundamental principles and involves devices that are similar for vehicles moving on land, on water, under water, in air, beyond the atmosphere within the gravitational field of earth and in space outside this field” [2]. The most rich and mature literature on guidance is probably found within the guided missile community. A guided missile is defined as a space-traversing unmanned vehicle that carries within itself the means for controlling its flight path [3]. Guided missiles have been operational since World War II [1]. Today, missile guidance theory encompasses a broad spectrum of guidance

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Nomenclature

C_x	drag coefficient
C_y	lift coefficient
C_z	lateral coefficient
D	diameter of maximum cross-section area (m)
F_x, F_y, F_z	components of total forces acting on missile (N)
F	fitness function
G	gravity force (N)
G_x, G_y, G_z	gravity force components (N)
I	moment of inertia (kg m^2/s)
I_x, I_y, I_z	moment of inertia components (kg m^2/s)
J	cost function (objective function)
k_p	proportional gain
k_i	integral gain
k_d	derivative gain
M_{THx}, M_{THy}, M_{THz}	thrust moment components (N m)
M_{Ax}, M_{Ay}, M_{Az}	aerodynamic moment components (N m)
M_x, M_y, M_z	components of total moments acting on missile (N m)
m	the mass of missile (kg)
m_{x0}, $m_{y\beta}$, m_{y0}, $m_{z\alpha}$, m_{z0}	aerodynamic moment coefficients
R_x, R_y, R_z	aerodynamic force components (N)
r	reference signal
S	reference area (m^2)
T	thrust force (N)
T_x, T_y, T_z	thrust force components (N)
V_m	missile velocity (m/s)
w	weight factor
X	range of missile (m)
X_g, Y_g, Z_g	ground coordinate
X_b, Y_b, Z_b	body coordinate
X_V, Y_V, Z_V	velocity coordinate
X_{cg}	distance between cg and the nozzle (m)
Φ, Ψ, γ	Euler's angles (°)
Φ_p	pitch demand programmer (°)
Ψ_p	yaw demand programmer (°)
α, β	angles of attack (°)
δ	fractional derivative
δ_α	jet deflection angle in the pitch plane (°)
δ_β	jet deflection angle in the yaw plane (°)
λ	fractional integration
$\omega_x, \omega_y, \omega_z$	angular velocity components (rad/s)

laws as classical guidance laws, optimal guidance laws, guidance laws based on fuzzy logic and neural network theory, differential geometric guidance laws and guidance laws based on differential game theory. Very interesting personal accounts of the guided missile development during and after World War II can be found in the literature [5,7,9]. Moreover, Locke and Westrum put the development of guided missile technology into a larger perspective [10,15].

Methodology

Mathematical model of the missile

The model constitutes the six degree of freedom (6-DOF) equations that break down into those describing kinematics, dynamics (aerodynamics, thrust, and gravity), command guidance generation systems, and autopilot (electronics, instruments, and actuators). The input to this model is launch conditions, target motion, and target trajectory characterization, while the outputs are the missile flight data (speed, acceleration, range, etc.) during engagement.

The basic frames needed for subsequent analytical developments are the ground, body and velocity coordinate systems. The origins of these coordinate systems are the missile center of gravity (cg). In the ground coordinate system, the X_g–Z_g lie in the horizontal plane and the Y_g axis completes a standard right-handed system and points up vertically. In the body coordinate system, the positive X_b axis coincides with the missile's center line and it is designated as roll-axis. The positive Z_b axis is to the right of the X_b axis in the horizontal plane and it is designated as the pitch axis. The positive Y_b axis points upward and it is designed as the yaw axis. The body axis system is fixed with respect to the missile and moves with the missile. In the velocity coordinate system, X_V coincides with the direction of missile velocity (V_m), which related to the directions of missile flight. The axis Z_V completes a standard right-handed system [4,6].

The pitch plane is X–Y plane, the yaw plane is X–Z plane, and the roll plane is Y–Z plane. The ground coordinate system and body coordinate system are related to each other through Euler's angles (Φ, Ψ, γ). The ground coordinate system and velocity coordinate system are related to each other through the angles (θ, σ). In addition, the velocity coordinate system is related to the body frame through the angle of attack (α) in the pitch plane and sideslip angle (β) in the yaw plane. The angles between different coordinate systems are shown in Fig. 1a [4,6].

The relation between the body and the velocity coordinate systems can be given as follows:

$$\begin{bmatrix} X_b \\ Y_b \\ Z_b \end{bmatrix} = \begin{bmatrix} \cos(\alpha)\cos(\beta) & \sin(\alpha) & -\cos(\alpha)\sin(\beta) \\ -\sin(\alpha)\cos(\beta) & \cos(\alpha) & \sin(\alpha)\sin(\beta) sin(\beta) 0 \cos(\beta) \end{bmatrix} \begin{bmatrix} X_V \\ Y_V \\ Z_V \end{bmatrix} \tag{1}$$

The body and velocity axes system as well as forces, moments and other quantities are shown in Fig. 1b.

There are 6 dynamic equations (3 for translational motion and 3 for rotational motion) and 6 kinematic equations (3 for translational motion and 3 for rotational motion) for a missile with six degrees of freedom. The equations are somewhat simpler, if the mass is constant. The missile 6-DOF equations in velocity coordinate system are given as following [4]:

$$F_x = m\dot{V}_m \tag{2}$$

$$F_y = mV_m\dot{\theta} \tag{3}$$

$$F_z = -mV_m\cos(\theta)\dot{\sigma} \tag{4}$$

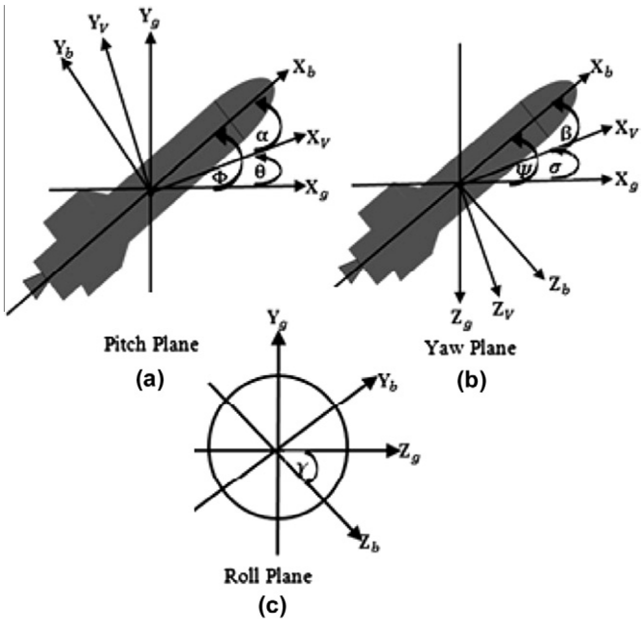

Fig. 1a The angles between different coordinate systems.

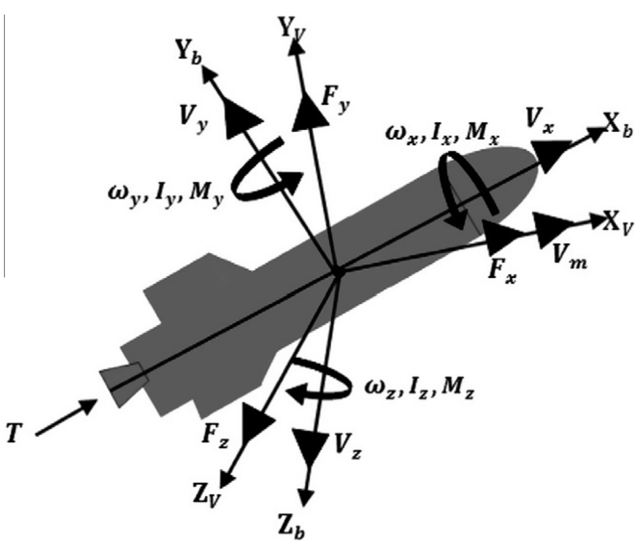

Fig. 1b Forces, moments and other quantities.

$$M_x = I_x\dot{\omega}_x - (I_y - I_z)\omega_y\omega_z \tag{5}$$

$$M_y = I_y\dot{\omega}_y - (I_z - I_x)\omega_z\omega_x \tag{6}$$

$$M_z = I_z\dot{\omega}_z - (I_x - I_y)\omega_x\omega_y \tag{7}$$

$$\dot{X} = V_m\cos(\theta)\cos(\sigma) \tag{8}$$

$$\dot{Y} = V_m\sin(\theta) \tag{9}$$

$$\dot{Z} = -V_m\cos(\theta)\sin(\sigma) \tag{10}$$

$$\dot{\Psi} = (\omega_y\cos(\gamma) - \omega_z\sin(\gamma))/\cos(\Phi) \tag{11}$$

$$\dot{\Phi} = \omega_y\sin(\gamma) + \omega_z\cos(\gamma) \tag{12}$$

$$\dot{\gamma} = \omega_x - \tan(\Phi)(\omega_y\cos(\gamma) - \omega_z\sin(\gamma)) = \omega_x - \dot{\Psi}\sin(\Phi) \tag{13}$$

In these equations, F_x, F_y, F_z are components of forces acting on missile in velocity coordinate system; M_x, M_y, M_z are moments acting on missile in body coordinate system; ω_x, ω_y, ω_z are angular velocity in body coordinate system; I_x, I_y, I_z are moments of inertia in body coordinate system; X is missile range; Y is missile altitude; Z is horizontal displacement of the missile; and m is missile mass. The forces and the moments acting on missile are due to thrust, aerodynamic and gravity that are given as following [4,6,8]:

$$F_x = T\cos(\alpha - \delta_\alpha)\cos(\beta - \delta_\beta) - QS(C_{x0} + C_x(\alpha^2 + \beta^2)) - mg\sin(\theta) \tag{14}$$

$$F_y = T\sin(\alpha - \delta_\alpha) + QSC_y\alpha - mg\cos(\theta) \tag{15}$$

$$F_z = -T\cos(\alpha - \delta_\alpha)\sin(\beta - \delta_\beta) - QSC_z\beta \tag{16}$$

$$M_x = DQSm_{x0}\frac{\omega_x D}{2V_m} \tag{17}$$

$$M_y = -T\cos(\delta_\alpha)\sin(\delta_\beta)X_{cg} + DQS\left(m_{y\beta}\beta + m_{y0}\frac{\omega_y D}{V_m}\right) \tag{18}$$

$$M_z = T\sin(\delta_\alpha)X_{cg} + DQS\left(m_{z\alpha}\beta + m_{z0}\frac{\omega_z D}{V_m}\right) \tag{19}$$

In these equations, C_x, C_{x0}, C_y, C_z are aerodynamic force coefficient; m_{x0}, $m_{y\beta}$, m_{y0}, $m_{z\alpha}$, m_{z0} are aerodynamic moment coefficients; D is the diameter of maximum cross-section area of body; S is the reference area; Q is the dynamic pressure; δ_α is the nozzle deflection angle in the pitch plane; δ_β is the nozzle deflection angle in the yaw plane; T is the thrust force; X_{cg} is the distance between the center of gravity (cg) and the nozzle; and g is acceleration due to gravity and is taken to be constant 9.81 m/s^2.

Fractional order PID controller design

In recent years, researchers reported that controllers making use of factional order derivatives and integrals could achieve performance and robustness results superior to those obtained with conventional (integer order) controllers. The fractional-order PID controller (FOPID) is the expansion of the conventional PID controller based on fractional calculus.

Theory of fractional calculus

The fractional calculus is a generalization of integration and derivation to non-integer order operator. We use the generalization of the differential and integral operators into one fundamental operator ${}_aD_t^\alpha$ where

$${}_aD_t^\alpha f(t) = \begin{cases} \frac{d^\alpha f(t)}{dt^\alpha} & \text{for } \mathbb{R}(\alpha) > 0 \\ 1 & \text{for } \mathbb{R}(\alpha) = 0 \\ \int_a^t f(\tau)(d\tau)^{-\alpha} & \text{for } \mathbb{R}(\alpha) < 0 \end{cases} \tag{20}$$

$\mathbb{R}(\alpha)$ denotes the real part of calculus order α which is a complex quantity. For our purpose, α is purely real a and t are the limits related to the operation of fractional differentiation [11,13].

The two definitions used for fractional differ integral are the Grunwald–Letnikov definition and the Riemann–Liouville definition:

- The Grunwald–Letnikov definition is given in Maiti et al. as follows [11]:

$$ {}_aD_t^{\alpha}f(t) = \lim_{T\to 0}\frac{1}{h^{\alpha}}\sum_{j=0}^{\left[\frac{t-a}{T}\right]}(-1)^j\binom{\alpha}{J}f(t-jT) \tag{21}$$

where

$$\binom{\alpha}{J} = \begin{cases} 1 & \text{for } j=0 \\ \frac{\alpha(\alpha-1)(\alpha-2)\cdots(\alpha-j+1)}{j!} & \text{for } j \geqslant 1 \end{cases}$$

and [x] means the integer part of x derived from the Grunwald–Letnikov definition, the numerical calculation formula of the fractional derivative can be achieved as follows [11]:

$$ {}_{t-L}D_t^{\alpha}f(t) \approx T^{-\alpha}\sum_{j=0}^{\left[\frac{L}{T}\right]} b_j f(t-jT) \tag{22}$$

where L is the length of memory and T is the sampling time (the step size of calculation). The binomial coefficient b_j can be calculated from the following formula:

$$b_j = \begin{cases} 1 & \text{for } j=0 \\ \left(1-\frac{1+\alpha}{j}\right)b_{j-1} & \text{for } j \geqslant 1 \end{cases} \tag{23}$$

- The Riemann–Liouville definition is given in [13] as follows:

$$ {}_aD_t^{\alpha}f(t) = \frac{1}{\Gamma(n-\alpha)}\frac{d^n}{dt^n}\int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-n+1}}d\tau \tag{24}$$

$$(n-1) < \alpha \leqslant n$$

where Γ is known Euler's gamma function and is given as

$$\Gamma(x) = \int_0^{\infty} e^{-t}t^{(x-1)}dt, \quad x>0 \tag{25}$$

with special case when $x = n$

$$\Gamma(n) = (n-1)(n-2)\cdots(2)(1) = (n-1)! \tag{26}$$

The Laplace transform of the fractional derivative of $f(t)$ is given in Maiti et al. as follows:

$$\mathcal{L}(D^{\alpha}f(t)) = S^{\alpha}F(S) - [D^{\alpha-1}f(t)]_{t=0} \tag{27}$$

where $F(S)$ is the Laplace transform $f(t)$. The Laplace transform of the fractional integral of $f(t)$ is given in Maiti et al. as follows:

$$\mathcal{L}(D^{-\alpha}f(t)) = S^{-\alpha}F(S) \tag{28}$$

Basic concepts of FOPID controller

The differential equation of the fraction PID controller is described in time domain by

$$u(t) = k_pe(t) + k_iD_t^{-\lambda}e(t) + k_dD_t^{\delta}e(t) \tag{29}$$

The continuous transfer function of the fraction PID controller is obtained through Laplace transform as

$$G_c(s) = k_p + k_iS^{-\lambda} + k_dS^{\delta} \tag{30}$$

It is obvious that the FOPID controller not only needs design three parameters k_p, k_i and k_d, but also design two orders λ, δ of integral and derivative controllers. The orders λ, δ are not necessarily integers, but any real numbers [11].

Fraction PID tuning by particle swarm optimization (PSO)

Optimization of fraction PID controllers firstly needs to design the optimization goal, the fitness function and then encode the parameters to be searched. PSO algorithm is running until the stop condition is satisfied. The best particle's position gives the optimized parameters [11].

The fraction PID controller has five parameters k_p, k_i, k_d, λ, and δ are required to be designed. Hence, the present problem of controller tuning can be solved by an application of the PSO algorithm for optimization on a five-dimensional solution space, each particle having a five-dimensional position and velocity vector. PSO needs to predefine numerical coefficients consisting of w (inertia weight factor) affects the ability of escaping from local optimization and refining global optimization; c_1 (self-confidence factor) and c_2 (swarm confidence factor) determines the ability of exploring and exploiting; swarm size balances the requirement of global optimization and computational cost; lastly, the topology concerns both the ability of sharing information and the expense of communication [11].

For getting good dynamic controller performance and avoiding large control input, the following control quality criterion is used [13]

$$J = \int_0^{\infty}(w_1|e(t)| + w_2e^2(t))dt \tag{31}$$

where w_1 and w_2 are non-negative weights, and $w_1 + w_2 = 1$. These weights can be either fixed or adapt dynamically during the optimization [13].

The fitness function evaluates the performance of particles to determine whether the best fitting solution is achieved. The fitness function is given as follows:

$$F = \frac{1}{J} \tag{32}$$

The stop criterion used was the one that defines the maximum number of generations to be produced. When PSO algorithm runs, the new populations generating process is finished, and the best solution to complete the generation number is the one among the individuals better adapted to the evaluation function [11,13].

Results and discussion

In this section, the autonomous flight of six degree of freedom flying body is simulated. The goal is to control the trajectory of the flight path of six degree of freedom flying body model using fractional PID controller. The design of fractional PID controller for six degree of freedom flying body is described. This design has been implemented in a simulation environment under Matlab's toolbox Simulink and results will be given and compared [12,14–16].

Model description

Missile thrust will be divided into two phases:

1. Boost phase: that will take about 5.8 s of total flight time ($0 \leqslant t < 5.8$ s) and thrust force $T = T_{\max}$.
2. Sustain phase: that will start after boost region until the impact with target ($5.8 \leqslant t < 25$ s) and thrust force $T = T_{\min}$.

The thrust force curve is shown in Fig. 2.

The nozzle deflection angle in pitch plane (δ_α) and yaw plane (δ_β) is limited with $\pm 28.5°$ (± 0.5 rad).

Building demand generator (reference trajectory)

The pitch demand programmer is an exponential command and is described as

$$\Phi_p = \Phi_{p0} - \Phi_S(1 - e^{-t/\tau p}) \tag{33}$$

where Φ_{p0} is the missile-launching angle with respect to the horizon; Φ_S are vertical position angles depending on target position. For our simulation $\Phi_{p0} = 35°$; $\Phi_S = 30°$; $\tau_p = 2.1788$ s.

The yaw demand programmer is an exponential command and is described as

$$\Psi_p = \Psi_s(1 - e^{-t/\tau\Psi}) \tag{34}$$

where Ψ_s is a horizontal position angle depending on target position. For our simulation $\Psi_s = 5°$; $\tau_\Psi = 0.2$ s.

Controller design

Fractional PID controller design

The fractional PID controller has five unknown parameters k_p, k_i, k_d, λ and δ that required to be designed. Hence, the present problem of controller tuning can be solved by an application of the PSO algorithm for optimization on a five-dimensional solution space, each particle having a five-dimensional position and velocity vector. The initial positions of the ith particles of the swarm can be represented by a five-dimensional vector, and then the initial values are randomly generated based on the extreme values.

Number of PSO particles in the population is 50. The inertia weight factor w decreases linearly from 0.9 to 0.4 (i.e. $w_{max} = 0.9$ and $w_{min} = 0.4$):

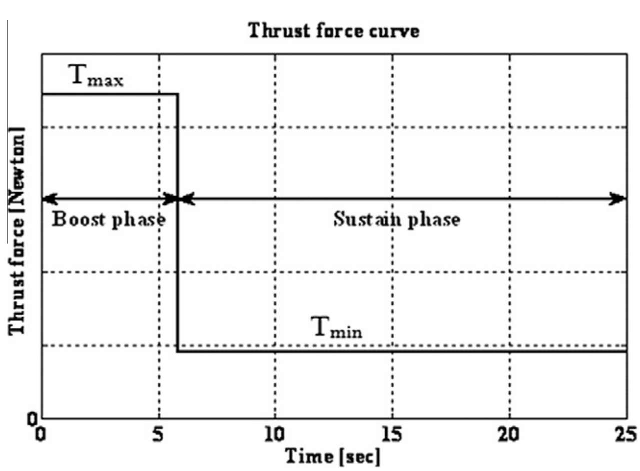

Fig. 2 Thrust force curve.

$$W = \frac{(w_{max} - w_{min}) \times (Iter_{max} - Iter_{now})}{Iter_{max}} + w_{min} \tag{35}$$

The self-confidence factor $c_1 = 0.12$ and swarm confidence factor $c_2 = 1.2$. The initial range of parameters are selected, these are $k_p \in [-300, 300]$, $k_i \in [-300, 300]$, $k_d \in [-300, 300]$, $\lambda \in [0, 1]$, $\delta \in [0, 1]$. The maximum number of generations is set as 200 (i.e. $Iter_{max} = 200$) [11,13].

After the stop criterion is met, i.e. after 100 runs of the PSO algorithm that is written in an m-file, the position vector of the best particle gives the optimized parameter of fractional PID controller as follows [11,13]:

- The fractional PID controller gains for pitch angle are
  $k_p = 234.9$, $k_i = 200$, $\lambda = 0.6568$, $k_d = 35.2$, $\delta = 0.5623$
- The fractional PID controller gains for yaw angle are
  $k_p = -53.95$, $k_i = -33.66$, $\lambda = 0.18$, $k_d = -21.26$, $\delta = 0.5623$

The negative gains in yaw channel are given by PSO algorithm since the yaw channel is located in the negative X–Z plane (negative Z-axis direction) as shown in Fig. 1a. Closed loop nonlinear system modeling using fractional PID controller is represented in Fig. 3.

Integer PID controller design

The PID controller has three unknown parameters k_p, k_i and k_d that required to be designed. Hence, the present problem of controller tuning can be solved by an application of the PSO algorithm for optimization on a three-dimensional solution space, each particle having a three-dimensional position and velocity vector. The initial positions of the ith particles of the swarm can be represented by a three-dimensional vector, and then the initial values are randomly generated based on the extreme values.

PSO factors are the same as in fractional PID tuning by PSO that are explained previously. The position vector of the best particle gives the optimized parameter of integer PID controller as following [11]:

- The PID controller gains for pitch angle are $k_p = 170.3$, $k_i = 11.86$, $k_d = 1.901$.
- The PID controller gains for yaw angle are $k_p = -50.84$, $k_i = -16.34$, $k_d =$ -1.138.

Fig. 4a gives pitch and yaw angles response of nonlinear system with fractional PID where pitch and yaw angle response tracks pitch and yaw demand program, respectively.

Fig. 4b shows pitch and yaw angles response of nonlinear system with PID where pitch and yaw angle response tracks pitch and yaw demand program, respectively.

The pitch error is the difference between pitch demand program (pitch reference trajectory) and pitch angle response. Fig. 5A refers to the pitch error comparison for PID and fractional PID. The pitch error with PID controller has high overshoot and does not reach a steady state. The pitch angle for PID controller is chattered at start of sustain phase (at $t = 5.8$ s). However, for pitch error with fractional PID controller has small overshoot and reaches the steady state faster.

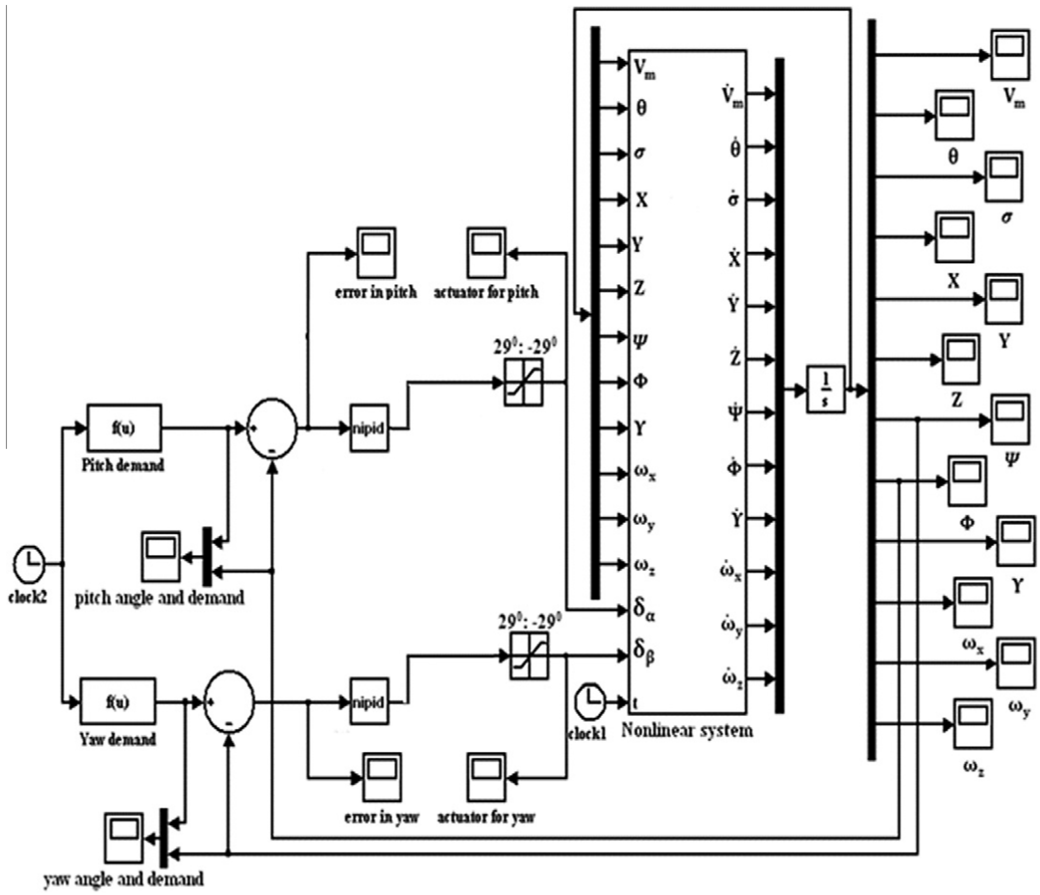

Fig. 3 Closed loop nonlinear system modeling using $PI^{\lambda}D^{\delta}$ controller.

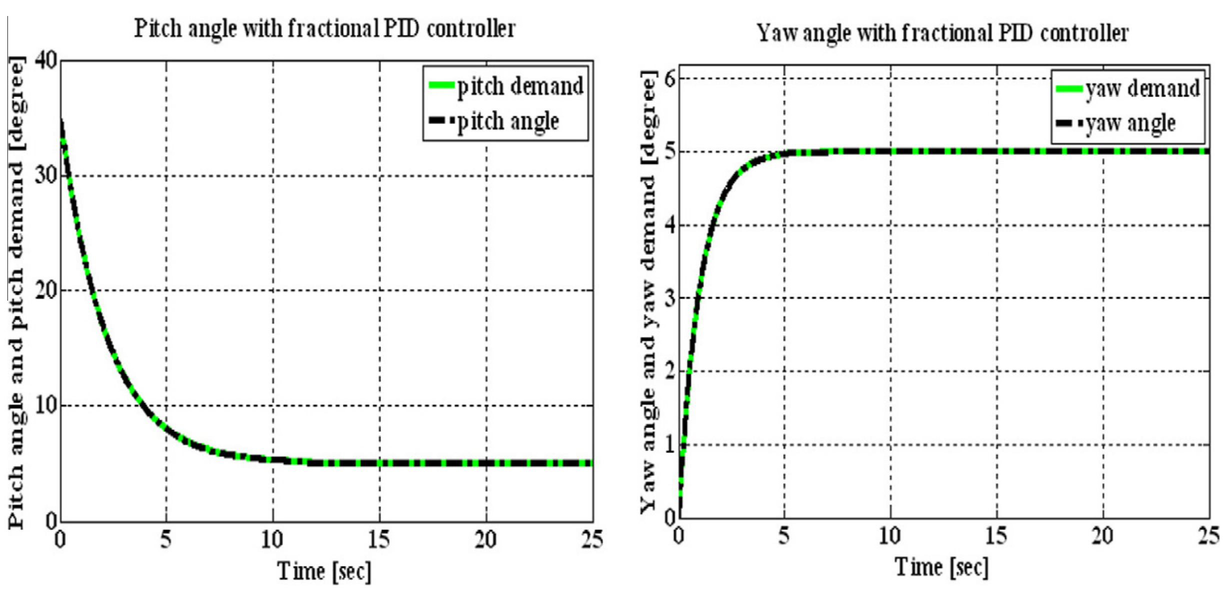

Fig. 4a Pitch and yaw angles with fractional PID controller vs. time.

The yaw error is the difference between yaw demand program (yaw reference trajectory) and yaw angle response. The yaw error with PID and fractional PID is represented in Fig. 5B. The yaw error with PID has high overshoot during boost phase and sustain phase. However, for yaw error with fractional PID controller has small overshoot.

Conclusion

The design of PID controller is acceptable where it gives good tracking with demand program but the design of fractional PID controller gives more accurate tracking with demand program. The design of fractional PID controllers gave the best

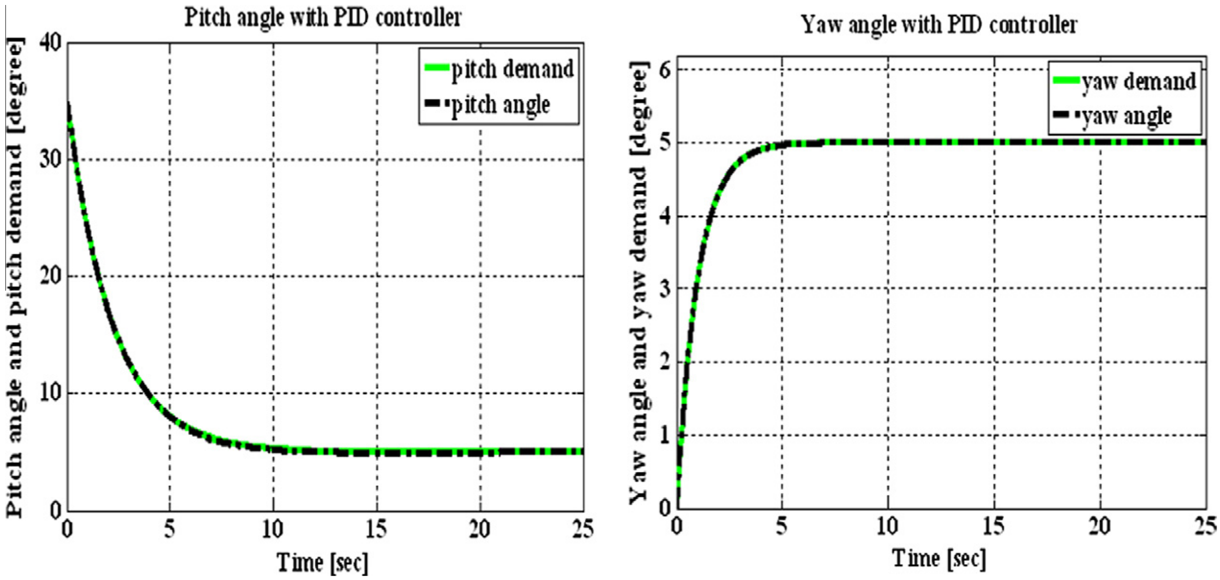

Fig. 4b Pitch and yaw angles with PID controller vs. time.

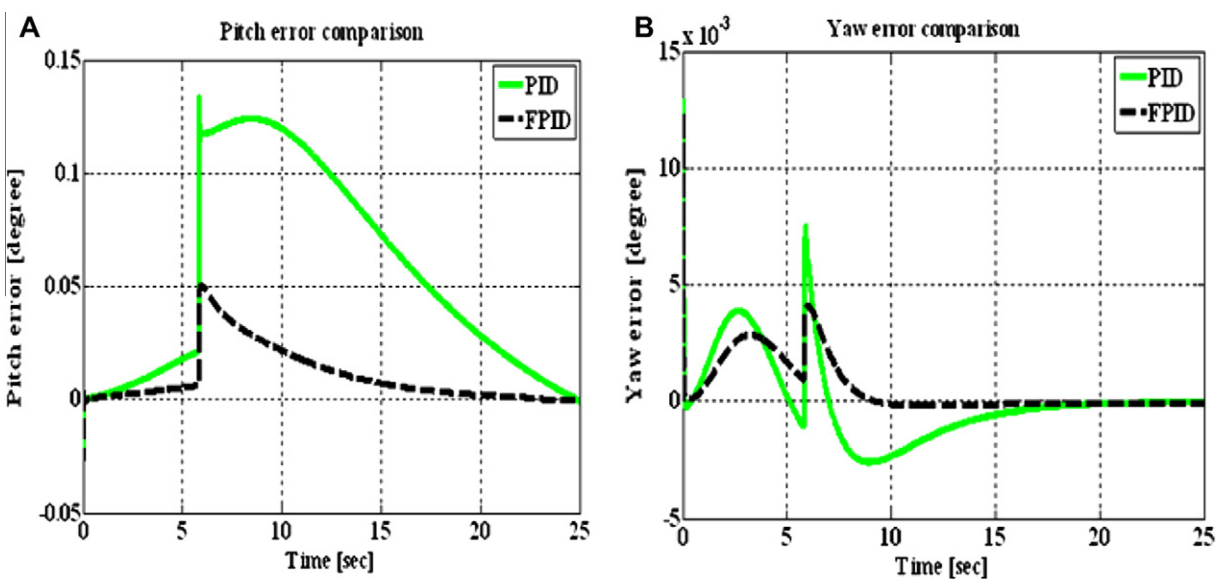

Fig. 5 Pitch error and yaw error comparisons with PID and fractional PID.

response for pitch and yaw angles since there are no steady state error, oscillation (chattering), and have small overshoot. The parameters optimization of fractional PID controllers based on PSO method was highly effective. According to optimization target, the PSO method could search the best global solution for fractional PID controllers' parameters and guarantee the objective solution space in defined search space.

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