Application of Intelligent Controller in Feedback Control Loop
for Aircraft Pitch Control

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Abstract: This paper presents the investigation into the development of hybrid control scheme for pitch control of aircraft system. Proportional-integral-derivative (PID) and PID-type fuzzy logic controller are used in this investigation to control the pitch angle of aircraft system. The dynamic modeling of system begins with a derivation of suitable mathematical model to describe the longitudinal motion of an aircraft. The main motivation behind this research is to investigate which approach provides the best performance base on time response specification and disturbances rejection for an autopilot of longitudinal dynamic in pitch aircraft. Through the simulation in Matlab and Simulink results shows that, the PID-type fuzzy logic controller perform the best performance compared to classical controller technique, Proportional-Integral-Derivative (PID).

Key words: Flight control, autopilot, pitch, longitudinal dynamic, PID, Fuzzy logic, PID-type fuzzy logic.

INTRODUCTION

One of the major problems of flight control system is due to the combination of nonlinear dynamics, modeling uncertainties and parameter variation in characterizing an aircraft and its operating environment. The aircraft motion in free flight is extremely complicated (Nelson, R.C., 1998). Generally, aircraft fly in three-axes plane by controoling aileron, rudder and elevator. They are designed to change and control the moments about the roll, pitch and yaw axes. The control system of the aircraft is divided into two portions, longitudinal and lateral control. In longitudinal control, the elevator controls pitch or the longitudinal motion of aircraft system. The pitch of aircraft is control by elevator which usually situated at the rear of the airplane running parallel to the wing that houses the ailerons. Pitch control is a longitudinal problem and this work presents on design an autopilot that controls the pitch of an aircraft. The autopilot is a pilot relief mechanism that assists in maintaining an attitude, heading, altitude or flying to navigation or landing references (Myint M. *et al.*, 2008). Designing an autopilot requires control system theory background and knowledge of stability derivatives at different altitudes and Mach numbers for a given aircraft (Shiau, J.K and Ma, D.M., 2009).

Lot of works has been done in (Zugaj, M. and Narkiewicz, J.J., 2010), (Khaleel, Q., 2010), (Wahid, N. *et al.*, 2010), (Chen, F.C. and Kalil, H.K., 1990) and (Ekprasit, P. and Sridhar, S., 2009), to control the pitch or longitudinal dynamic of an aircraft for the purpose of flight stability and this research still remains an open issue in the present and future works. Tools of computational intelligent such as fuzzy logic controller have been used in various applications including in the pitch control and it is convenient to implement in the complex process, (Lee, C.C., 1990) and (Lee, C.C., 1990). Several previous works on improving fuzzy logic controller can be found in (Arrofiq, M. and Saad, N., 2010), (Kuzelkaya, M. *et al.*, 2003) and (Woo, Z.W. *et al.*, 2000). (Vick, A. and Cohen, K., 2009) develop a PID based fuzzy logic pitch attitude hold system for a typical fighter jet under a variety of performance conditions including approach, subsonic cruise and supersonic cruise. In (Edgar, N. *et al.*, 2007), the synthesis of different flight controllers are developed on two hybrid intelligent control systems combining computational intelligence methodologies with other control techniques for altitude control of aircraft.

The main purpose of this study is to develop a conventional PID controller and hybrid intelligent control scheme, PID-type fuzzy logic controller to control the pitch of an aircraft system. PID controllers are commonly used in many control system because of their simple structures and intuitionally comprehensible control algorithms (Namazov, M. and Basturk, O., 2010). In this paper PID-type fuzzy logic controller is introduced, taking the advantages of fuzzy logic and PID controller. The performance of both control schemes, PID and PID-type FLC with respect to the pitch angle of aircraft longitudinal dynamics are investigated. Simulation is developed within Simulink and Matlab for evaluation of the control strategies. In this work, the dynamic model of the pitch longitudinal dynamics is derived in the transfer function and state-space forms. To demonstrate the

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effectiveness of the purposed control schemes, the disturbance effect is applied to the system. Finally, a comparative assessment of the impact of each controller on the system performance is presented and discussed.

Modelling of a Pitch Control:

In order to reduce the complexity of analysis, under certain assumptions, the equation governing motion of an aircraft can be separated into two groups, namely the longitudinal and lateral equations. This section provides a brief description on the modelling of pitch control longitudinal equation of aircraft, as a basis of a simulation environment for development and performance evaluation of the proposed controller techniques. The system of longitudinal dynamics is considered in this investigation and derived in the transfer function and statespace forms. The pitch control system considered in this work is shown in Figure 1 where X_b, Y_b and Z_b represent the aerodynamics force components. θ, Φ and δe represent the orientation of aircraft (pitch angle) in the earth-axis system and elevator deflection angle.
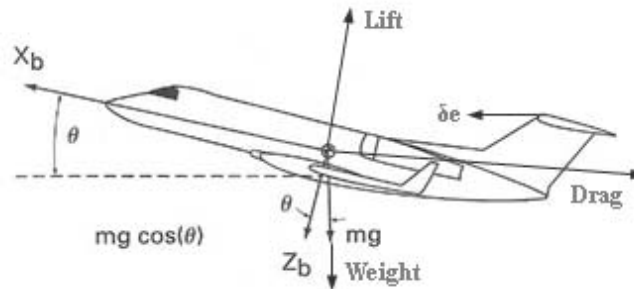

Fig. 1: Description of pitch control system.

Figure 2 shows the forces, moments and velocity components in the body fixed coordinate of aircraft system. The aerodynamics moment components for roll, pitch and yaw axis are represent as L, M and N. The term p, q, r represent the angular rates about roll, pitch and yaw axis while term u, v, w represent the velocity components of roll, pitch and yaw axis. α and β are represents as the angle of attack and sideslip. In this study the data from General Aviation Airplane (Nelson, R.C., 1998) is used in system analysis and modeling.
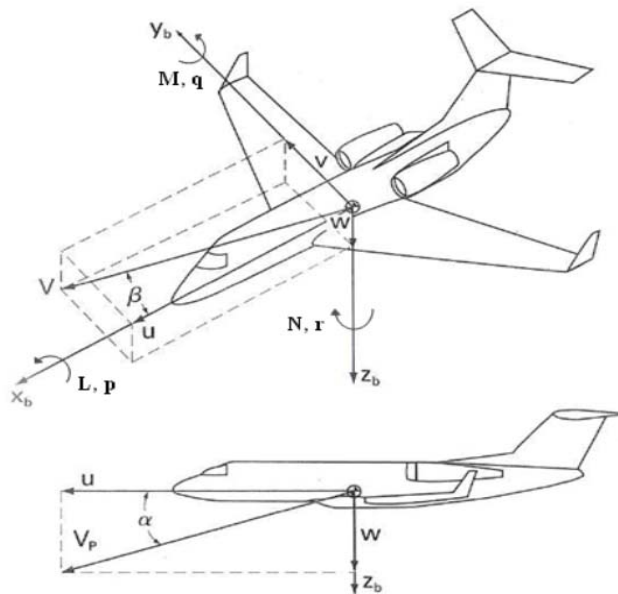

Fig. 2: Definition of force, moments and velocity in body fixed coordinate.

A few assumption need to be considered before continuing with the modeling process. First, the aircraft is steady state cruise at constant altitude and velocity, thus the thrust and drag are cancel out and the lift and weight balance out each other. Second, the change in pitch angle does not change the speed of an aircraft under any circumstance. Referring to the Figure 1 and Figure 2, the following dynamic equations include force and

moment equations are determined as shown in equation (1), (2) and (3). Referring to the Figure 1 and Figure 2, the following dynamic equations include force and moment equations are determined.

The longitudinal stability derivatives parameter used are denoted in Table I.

Table 1: Longitudinal Derivative Stability Parameters.

Longitudinal Derivatives	Components		
	Dynamics Pressure and Dimensional Derivative $Q = 36.8$lb/ft^2, $QS = 6771lb$, $QS\overline{C} = 38596ft.lb$, ($\overline{c}/2u_0$) = 0.016s		
	X-Force, (S^{-1})	Z-Force, (F^{-1})	Pitching Moment, (FT^{-1})
Rolling velocities	$X_u = -0.045$	$Z_u = -0.369$	$M_u = 0$
Yawing velocities	$X_w = 0.036$	$Z_w = -2.02$	$M_w = -0.05$
	$X_{\dot{w}} = 0$	$Z_{\dot{w}} = 0$	$M_{\dot{w}} = -0.051$
Angle of attack	$X_\alpha = 0$	$Z_\alpha = -355.42$	$M_\alpha = -8.8$
	$X_{\dot\alpha} = 0$	$Z_{\dot\alpha} = 0$	$M_{\dot\alpha} = -0.8976$
Pitching rate	$X_q = 0$	$Z_q = 0$	$M_q = -2.05$
Elevator deflection	$X_{\delta e} = 0$	$Z_{\delta e} = -28.15$	$M_{\delta e} = -11.874$

$$X - mgS_\theta = m(\dot{u} + qv - rv) \tag{1}$$

$$Z + mgC_\theta C_\Phi = m(\dot{w} + pv - qu) \tag{2}$$

$$M = I_y\dot{q} + rq(I_x - I_z) + I_{xz}(p^2 - r^2) \tag{3}$$

Equation (1), (2) and (3) should be linearized using small disturbance theory. The equations are replaced by a variable or reference value plus a perturbation or disturbance, as shown in below:

$$u = u_o + \Delta u \quad v = v_o + \Delta v \quad w = w_o + \Delta w$$

$$p = p_o + \Delta p \quad q = q_o + \Delta q \quad r = r_o + \Delta r$$

$$X = X_o + \Delta X \quad M = M_o + MY \quad Z = Z_o + \Delta Z$$

$$\delta = \delta_o + \Delta\delta \tag{4}$$

For convenience, the reference flight condition is assumed to be symmetric and the propulsive forces are assumed to remain constant. This implies that,

$$v_0 = p_0 = q_0 = r_0 = \Phi_0 = \psi_0 = w_0 = 0 \tag{5}$$

After linearization, the equation (6), (7) and (8) are obtained.

$$\left(\frac{d}{dt} - X_u\right)\Delta u - X_w\Delta w + (g\cos\theta_o)\Delta\theta = X\delta_e\Delta\delta_e \tag{6}$$

$$-Z_u\Delta u + \left[(1-Z_w)\frac{d}{dt} - Z_w\right]\Delta w - \left[(u_o + Z_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta = Z_{\delta e}\Delta\delta_e \tag{7}$$

$$-M_u\Delta u - \left(M_w\frac{d}{dt} + M_w\right)\Delta w + \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta = M_{\delta e}\Delta\delta_e \tag{8}$$

By manipulating the (6), (7), (8) and substituting the parameters values of the longitudinal stability derivatives, the following transfer function for the change in the pitch rate to the change in elevator deflection angle is shown as obtained in equation (9).

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-(M_{\delta e} + M_{\dot\alpha}Z_{\delta e}/u_0)s - (M_\alpha Z_{\delta e}/u_0 - M_{\delta e}Z_\alpha/u_0)}{s^2 - (M_q + M_{\dot\alpha} + Z_\alpha/u_0)s + (Z_\alpha M_q/u_0 - M_\alpha)} \tag{9}$$

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.

$$\Delta q = \Delta \dot{\theta} \tag{10}$$

$$\Delta q(s) = s \Delta \theta(s) \tag{11}$$

$$\frac{\Delta \theta(s)}{\Delta \delta_e(s)} = \frac{1}{s} \cdot \frac{\Delta q(s)}{\Delta \theta(s)} \tag{12}$$

Therefore the transfer function of the pitch control system is obtained in equation (13) and (14) respectively.

$$\frac{\Delta \theta(s)}{\Delta \delta_e(s)} = \frac{1}{s} \cdot \frac{-(M_{\dot{\alpha}} + M_{\dot{\alpha}} Z_{\dot{\alpha}} / u_0)s - (M_{\alpha} Z_{\dot{\alpha}} / u_0 - M_{\dot{\alpha}} Z_{\alpha} / u_0)}{s^2 - (M_q + M_{\dot{\alpha}} + Z_{\alpha} / u_0)s + (Z_{\alpha} M_q / u_0 - M_{\alpha})} \tag{13}$$

$$\frac{\Delta \theta(s)}{\Delta \delta_e(s)} = \frac{11.7304\,s + 22.578}{s^3 + 4.9676\,s^2 + 12.941s} \tag{14}$$

The transfer function can be represented in state-space form and output equation as state by (15) and (16).

$$\begin{bmatrix} \Delta \dot{\alpha} \\ \Delta \dot{q} \\ \Delta \dot{\theta} \end{bmatrix} = \begin{bmatrix} -2.02 & 1 & 0 \\ -6.9868 & -2.9476 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta q \\ \Delta \theta \end{bmatrix} + \begin{bmatrix} 0.16 \\ 11.7304 \\ 0 \end{bmatrix} [\Delta_{\dot{\alpha}}] \tag{15}$$

$$y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta \alpha \\ \Delta q \\ \Delta \theta \end{bmatrix} + [0] \tag{16}$$

Methodology: Controller Design:

In this section, two control schemes for aircraft pitch control are proposed and described in detail. Initially the PID and PID-type fuzzy logic controller is designed in the closed-loop system for control the pitch of an aircraft.

PID Controller:

A proportional integral derivative controller (PID) is a generic control loop feedback mechanism widely used in industrial control systems and regarded as the standard control structures of the classical control theory. Figure 3 shows the control system of schematic model with general PID controller.
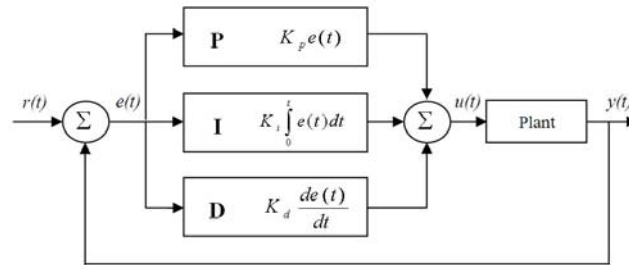
Fig. 3: PID configuration.

The mathematical description of linear relationship exist between the controller output, *u(t)* and the error, *e(t)* is expressed as equation (17) and (18) where K_p = proportional gain, K_i = integral gain, K_d = derivative gain, T_i = integral time and T_d = derivative time.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{17}$$

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{18}$$

The implementation of PID control method is done by adjusting the value of gain K_p, K_i and K_d in order to get the best response of the system. The selection of these values will cause for variation in observed response with respect to desired response. The transfer function of the pitch control was developed earlier is used and shown in equation (14). In this work the controller parameters of PID controller a set to *K_p=4.15, K_i=0.04 and K_d=0.9.*

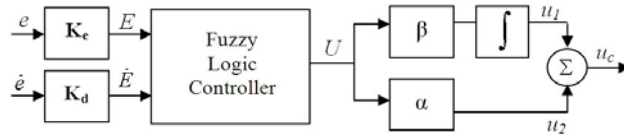### Structure of Fuzzy Logic Controller:

Fuzzy logic controllers fall into the class of intelligent control system. An intelligent control system combines the technique from the field of artificial intelligent with those of control engineering to design autonomous system that can sense, reason and plan, learn and act in intelligent manner (Kisabo, A.B. *et al*., 2011). Basically, fuzzy controller comprises of four main components, fuzzification interface, knowledge base, inference mechanism and defuzzification interface. Figure 4 shows components of fuzzy logic controller.
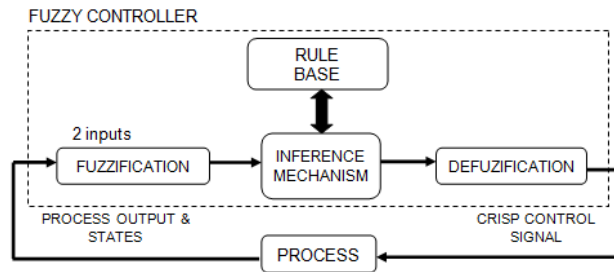
Fig. 4: Components of fuzzy logic controller.

PID-type Fuzzy Logic Controller

A PID-type fuzzy logic controller is develop to control the rigid body motion of the system. The common structure of PID-type fuzzy controller that has two inputs and rules base is depicted in Figure 5. As can be seen from Figure 5, the output from controller, u_c is fed by integrator output, u_1 and gain, u_2.

Fig. 5: PID-type fuzzy logic controller.

The output of PID-type fuzzy controller is given by equation (19).

$$u_c = \alpha U + \beta\int U dt \tag{19}$$

From work that has been done in (Qiou W.Z. and Mizumoto M., 1996), the relation between input and output variables of fuzzy parameters is given by equation (20).

$$U = A + PE + D\dot{E} \tag{20}$$

The term *$E=K_e.e$* and *$E=K_d.\dot{e}$*. Therefore from equation (19) and (20), the controller output of PID-type fuzzy is obtained in equation (21).

$$u_c = \alpha A + \beta At + \alpha K_e Pe + \beta K_d De + \beta K_e P\int edt + \alpha K_d D\dot{e} \tag{21}$$

The hybrid fuzzy control system used in this work is shown in Figure 6 where K_e, K_d, β and α are scaling factors for two inputs and one outputs of the fuzzy logic controller used with normalized universe of discourse for the fuzzy membership function. The K_e and K_d are the error input and change of error input gains, while β

and α are output gains respectively. The inputs to the PID-type fuzzy logic controller are the error, *e* which measures the system performance and the rate at which the error changes, $\dot{e}$ whereas the output is the control signal, u_c. The hybrid fuzzy control system proposed in this work is shown in Figure 6.
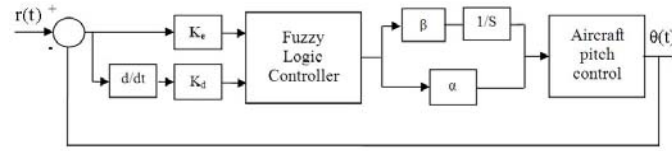
Fig. 6: Closed-loop control structure of PID-type fuzzy logic controller.

For PID-type FLC, the triangular and trap membership function are chosen for pitch angle error, pitch angle error rate and control output. Scaling factors, K_e and K_d, are chosen two convert the two inputs within the universe of discourse and activate the rule base respectively, whereas β and α, is selected to activates the system and generate the desired output. All these scaling factors are chosen based on testing method.

Fuzzification involves the conversion of the input and output signal into a number of fuzzy represented values (fuzzy set). Each fuzzy set consists of three types membership function, which is negative (N), zero (Z) and positive (P). The appropriate membership function to represent each fuzzy set need to be defined and each fuzzy set must have the appropriate universe of discourse. In addition, the membership functions are evenly distributed so that the tuning process of the controller can be easily done. In designing PID-type FLC, the standard fuzzy rules generated from the under damped response curve. This response is transform into fuzzy rules using the formula obtained in equation (21) and (22) below.

$$e(k) = r(k) - y(k) \tag{21}$$

$$\dot{e}(k) = e(k) - e(k-1) \tag{22}$$

In this work, two inputs and one output of PID-type FLC pitch control can be designed by defining error as the reference angle minus the measured angle and implementing the expert knowledge in a form of IF-THEN rule structure. These are nine rules that have been utilized as a closed-loop component in designing the PID-type FLC for maintaining pitch angle of aircraft system as defined in Table 2. The control surface of this control scheme is shown in Figure 7. The four scaling factors, K_e, K_d, β and α, are chosen to achieve satisfactory set of time domain parameters. The value are recorded as, $K_e=1.5$, $K_d=0.25$, $\beta=0.05$ and $\alpha=4$.

Table 2: Rules of the PID-type Fuzzy Logic Controller.

No.	Rules
1.	If (e is N) and ($\dot{e}$ is N) then (u is N)
2.	If (e is N) and ($\dot{e}$ is Z) then (u is N)
3.	If (e is N) and ($\dot{e}$ is P) then (u is N)
4.	If (e is Z) and ($\dot{e}$ is N) then (u is N)
5.	If (e is Z) and ($\dot{e}$ is Z) then (u is Z)
6.	If (e is Z) and ($\dot{e}$ is P) then (u is P)
7.	If (e is P) and ($\dot{e}$ is N) then (u is P)
8.	If (e is P) and ($\dot{e}$ is Z) then (u is P)
9.	If (e is P) and ($\dot{e}$ is P) then (u is P)

Implementation and Results:

In this section, the proposed of control schemes are implemented and the corresponding results are presented. A unit step command is required in order for pitch angle to follow the reference value of 0.2 radian = 11.5 degree. Matlab/Simulink model block diagram of pitch control system used in this work is shown in Figure 8.
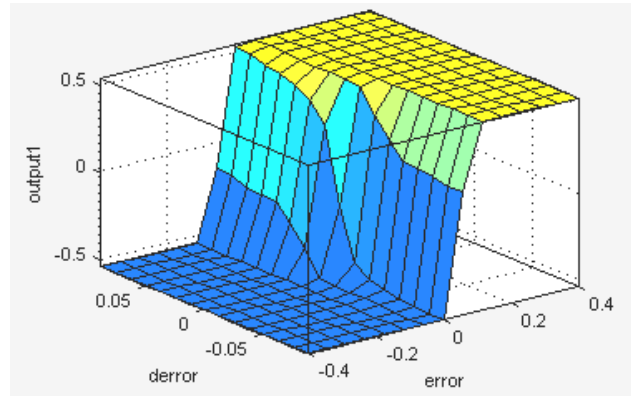
**Fig. 7:** Control surface of PID-type fuzzy logic controller.
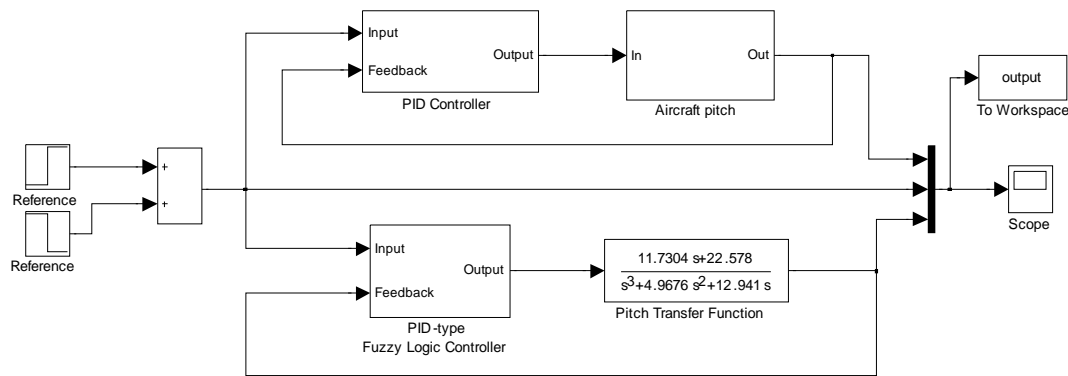
**Fig. 8:** Simulink model for pitch control system.

System response namely pitch angle are observed in this work. The performances of hybrid fuzzy logic controller are assessed in term of time response specification and performance of disturbances rejection in comparison to the classical PID controller. The system response of pitch control system with the proportional-integral-derivative (PID) is shown in Figure 9. By referring to the Figure 9, the result demonstrates that PID controller achieved steady-state response with the delay time of 0.24 s, settling time of 1.1 s and rising time of 2.726 s. Furthermore the PID controller tends to produce small steady state error (E_{ss}) that is 0.001% and 0% of overshoot. This can be indicating that PID controller can handle the effect of disturbances in the system.

Figure 10 shows the closed loop system response for pitch control system under PID-type fuzzy logic controller. Two inputs have been applied to PID-type fuzzy logic controller which is the error, e that computed by comparing the reference point, desired pitch angle with the plant output and the change of error, $\dot{e}$ which generated by the derivation of the error. As depicted from Figure 10, it can be observed that the pitch angle follows the reference value respectively. The PID-type fuzzy logic controller is able to give a good response without produce any overshoot. The response is comparatively faster compared to PID controller with the delay time, T_d about 0.166 s, settling time, T_s about 0.356 s and rise time, T_r about 0.64 s. The results also demonstrated that the hybrid PID-type fuzzy logic controller can eliminate the effect of disturbances in the system up to 0.001%.

Figure 11 shows the performance of both control schemes with respect to the step reference input signal. The system responses performances are compared between PID controller and PID-type fuzzy logic controller. The summary for the performance characteristics of the step response for the pitch angle between PID and PID-type fuzzy logic controller is shown in Table 3 quantitatively. For comparative assessment, the results clearly shows that PID-type fuzzy logic controller has the best performance and achieved better tracking response than conventional PID controller. It is indicated from faster delay time, faster settling time and faster rising time. At the same time, both control schemes produces the output response with less steady-state error and without overshoot. Therefore, from the result obtained in Figure 11, it can be concluded that PID-type fuzzy logic controller provide better performance in controlling the pitch angle as compared to the PID controller.
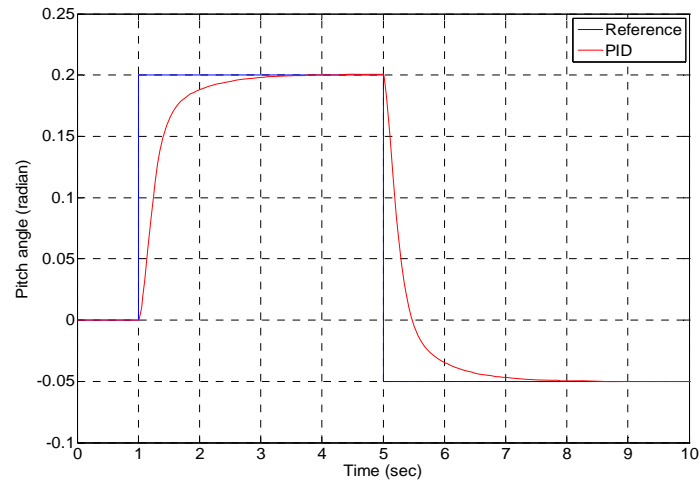
Fig. 9: Pitch angle response with PID controller.
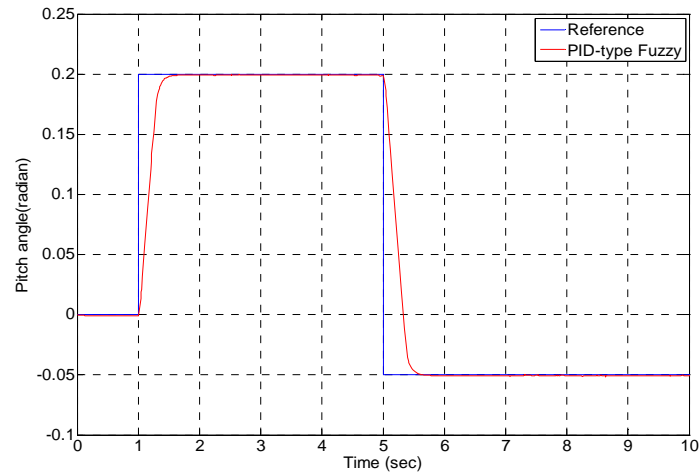
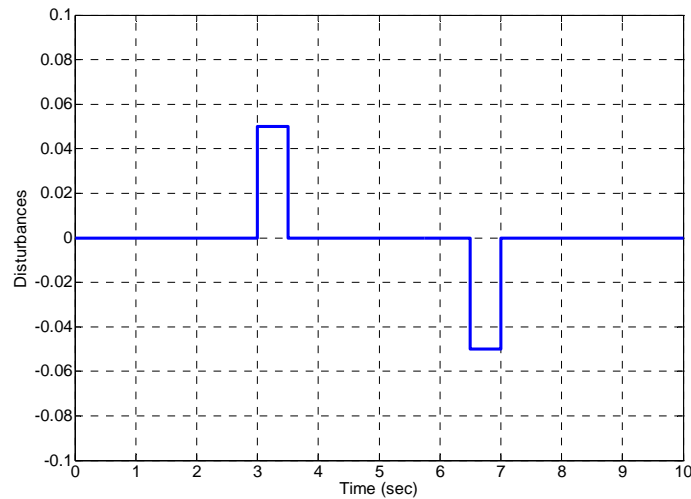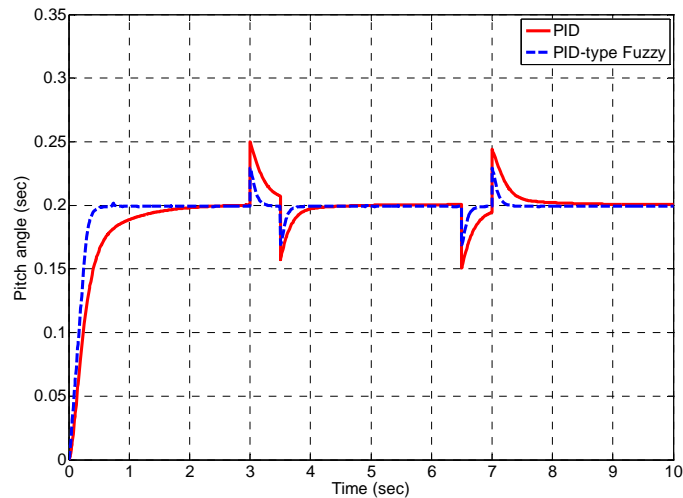**Fig. 10:** Pitch angle response with PID-type fuzzy logic controller.
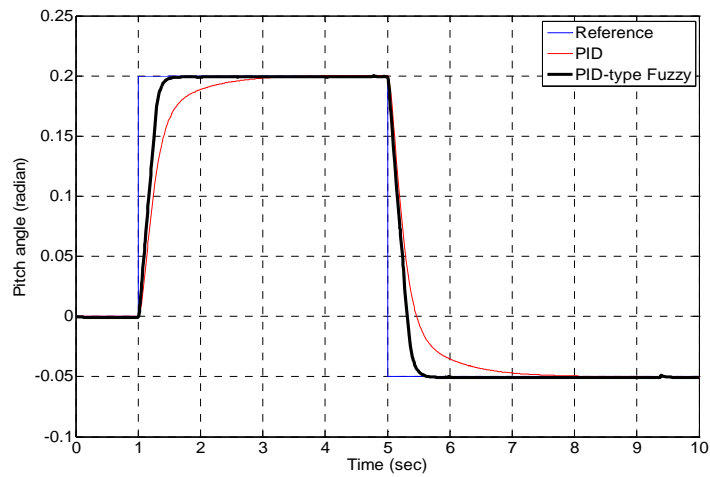
Fig. 11: Pitch angle response with PID and PID-type fuzzy logic controller.

Table 3: Summary of performance characteristics of pitch angle.

Response characteristic	Pitch angle	
	PID	PID-type FLC
Delay time, T_d	0.24 s	0.166 s
Rising time, T_r	2.726 s	0.64 s
Settling time, T_s	1.1 s	0.356 s
Percent overshoot, % OS	0	0
Steady-state error, e_{ss}	0.001	0.001

The following result, evaluate the output response of the closed-loop system to the disturbances applied as shown in Figure 12. The output response of pitch angle with the presence of disturbances is shown in Figure 13. From Figure 13, it can be conclude that, the performance of output response in disturbances cancellation with PID-type FLC is better compared to performance output from PID controller with settling time, $T_s = 0.099$ s and 0.098 s while PID, $T_s = 0.254$ s and 0.343 s.

Fig. 12: Disturbances

Fig. 13: Pitch angle response in disturbances rejection.

Conclusion:

The development and investigation of pitch control system with disturbances effect using PID and PID-type fuzzy logic controller have been presented in this paper. Pitch control of an aircraft is a system which requires a pitch controller to maintain the angle at it desired value. The proposed control schemes have been implemented within simulation environment in Matlab and Simulink. Performance of the control schemes has been evaluated in term of time domain specification and disturbances cancellation. The results obtained, demonstrate that the effect of the disturbances in the system can successfully be handled by PID and PID-type fuzzy logic controller.

Based on the results, the system responses indicate the performance of pitch control system using PID-type fuzzy logic controller has been improved and satisfied compared to PID controller. For further research, effort can be extended and devoted through adding another element that makes up the control system, following by adopted the control scheme in practical application.

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