Longitudinal Control of an Aircraft Using Artificial Intelligence

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***Abstract*— In industrial control processes and in flight control systems PID have been widely used because of their simple structure and robust performance in a wide range of operating conditions. Along with classical controller artificial intelligence such as Fuzzy Logic Controller (FLC) algorithms have been used for the optimum design of PID controllers. In this paper, Hybrid Fuzzy PID controller is developed to improve the performance for longitudinal control of an aircraft dynamics. The hybrid controller is designed based on the dynamic modelling of an aircraft system begins with a derivation of suitable mathematical model to describe the longitudinal dynamics. Matlab-Simulink model is used to tune each parameter of Proportional-integral-derivative (PID) controller by selecting appropriate fuzzy rules through simulations. Mamdani-type of Fuzzy Logic Controller is employed in this paper due to its simple and robust approach. The simulation results shows that Hybrid Controller tuned by PID algorithm is better in performance and more robust than the classical type algorithm for aircraft pitch control.**

Keyword- Fuzzy logic, Fuzzy sets, Pitch dynamics, Hybrid Controller, PID controller.

I. INTRODUCTION

The response of aerospace vehicles to perturbations in their flight environments and to control inputs [1-3] deals mainly with dynamics characteristics of flight. To characterize the aerodynamic and propulsive forces and moments acting on the vehicle, and the dependence of these forces and moments on the flight variables, including airspeed and vehicle orientation is the main objective of aircraft dynamics. The rapid advancement of aircraft design from the very limited capabilities of the Wright brothers first successfully airplane to today's high performance military, commercial and general aviation aircraft require the development of many technologies, these are aerodynamics, structures, materials, propulsion and flight control. In longitudinal control, the elevator controls pitch or the longitudinal motion of aircraft system [4]. Pitch is controlled by the rear part of the tail plane's horizontal stabilizer being hinged to create an elevator. By moving the elevator control backwards the pilot moves the elevator up a position of negative camber and the downwards force on the horizontal tail is increased. The angle of attack on the wings increased so the nose is pitched up and lift is generally increased. In gliders the pitch action is reversed and the pitch control system is much simpler, so when the pilot moves the elevator control backwards it produces a nose-down pitch and the angle of attack on the wing is reduced. The pitch angle of an aircraft is controlled by adjusting the angle and therefore the lift force of the rear elevator. Lot of works has been done in the past to control the pitch of an aircraft for the purpose of flight stability and yet this research still remains an open issue in the present and future works [6 -7].

II. MATHEMATICAL MODEL OF LONGITUDINAL CONTROL

The notation [8] for describing the aerodynamic forces and moments acting upon, flight vehicle is indicated in figure 1. The variables x, y, z represent coordinates, with origin at the centre of mass of the vehicle. The x-axis [9] points toward the nose of the vehicle. The z-axis is perpendicular to the x-axis, and pointing approximately down. The y axis completes a right-handed orthogonal system, pointing approximately out the right wing [10].

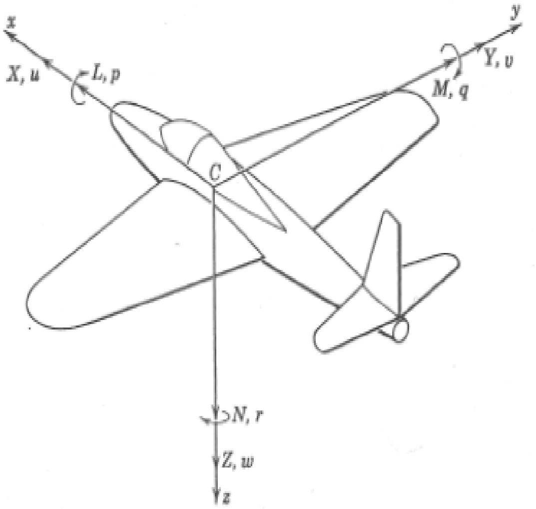


Fig. 1 Force, moments, and velocity components in a body fixed coordinate

Angles θ, φ and δ_e represent the orientation of aircraft pitch angle and elevator deflection angle. The forces, moments and velocity components in the body fixed coordinate are showed in Fig. 1. 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. The angles α and β represents the angle of attack and sideslip respectively [11 -13].

The atmosphere in which the plane flies is assumed undisturbed, thus forces and moment due to atmospheric disturbance are considered zero. Hence, considering Fig. 1, the following dynamic equations describe the longitudinal dynamics of a typical aircraft;

Force equations:

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

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

Momentum equation:

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

Equation 1, 2 and 3 should be linearized using small disturbance theory. The equations are replaced by a reference value plus a perturbation or disturbance, as given in equation 4. All the variables in the equation of motion are replaced by a reference value plus a perturbation or disturbance. The perturbations in aerodynamic forces and moments are functions of both, the perturbations in state variables and control inputs.

$$\begin{gathered} u = u_0 + \Delta u,\ v = v_0 + \Delta v,\ w = w_0 + \Delta w \\ p = p_0 + \Delta p, q = q_0 + \Delta q, r = r_0 + \Delta r \\ X = X_0 + \Delta X,\ M = M_0 + \Delta M,\ Z = Z_0 + \Delta Z \\ \delta = \delta_0 + \Delta\delta \end{gathered} \tag{4}$$

For convenience, the reference flight condition is assumed to be symmetric and the propulsive forces are assumed to remain constant [14]. This implies that,

$$v_0 = p_0 = q_0 = r_0 = \varphi_0 = \psi_0 = w_0 = 0 \tag{5}$$

After linearization the following equations were obtained for the longitudinal dynamics, of the aircraft.

$$\left[\frac{d}{dt} - X_u\right] u + g_o \cos\theta_0 - X_w w = X_{\delta e}\delta_e + X_{\delta T}\delta_T \tag{6}$$

$$-Z_u u + \left[(1 - Z_{\dot{w}})\frac{d}{dt} - Z_W\right] w - \left[u_0 + Z_q\right] q + g_o \sin\theta_0 = Z_{\delta e}\delta_e + Z_{\delta T}\delta_T \tag{7}$$

$$-M_u u - \left[(M_{\dot{w}})\frac{d}{dt} - M_W\right] w + \left[\frac{d}{dt} - M_q\right] q = M_{\delta e}\delta_e + M_{\delta T}\delta_T \tag{8}$$

The equation 9 gives the transfer function for the change in the pitch rate to the change in elevator deflection angle.

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

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 as given in equation 10, 11 and 12.

$$\Delta q = \Delta\,\dot{\theta} \qquad (10)$$

$$\Delta q(s) = s\Delta\theta(s) \qquad (11)$$

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

Hence, the transfer function for the pitch system dynamics of an aircraft can be described by,

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{1}{s}\frac{-\left(M_{\delta e+}\frac{M_{\dot{\alpha}}Z_{\delta e+}}{u0}\right)s-\left(\frac{M_{\alpha}Z_{\delta e+}}{u0}-\frac{Z_{\alpha}M_{\delta e}}{u0}\right)}{s^2-\left(M_q+M_{\dot{\alpha}}+\frac{Z_{\alpha}}{u_0}\right)s+\left(\frac{Z_{\alpha}M_q}{u_0}-M_{\alpha}\right)} \qquad (13)$$

For simplicity, a first order model of an actuator is employed with the transfer function as given in equation 14, and time constant τ = 0.0167sec is employed.

$$H(s) = \frac{1}{\tau s+1} \qquad (14)$$

Modern computer-based flight dynamics simulation is usually done in dimensional form, but the basic aerodynamic inputs are best defined in terms of the classical non-dimensional aerodynamic forms. These are defined using the dynamic pressure,

$$Q = \frac{1}{2}\rho V^2 = \frac{1}{2}\rho SLV_{eq}^2 \qquad (15)$$

Where ρ is the ambient density at the flight altitude and Veq is the equivalent airspeed, which is defined by the above equation in which ρSL, is the standard sea-level value of the density. In addition, the vehicle reference area S, usually the wing platform area, wing mean aerodynamic chord $\overline{c}$, and wing span b are used to non-dimensionalize forces and moments.

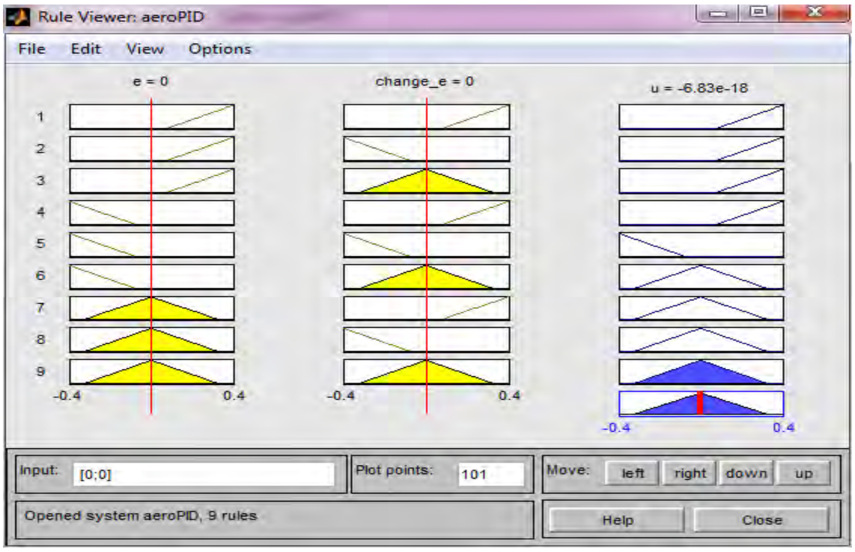
III. PID AND MAMDANI FUZZY LOGIC COMBINATIONS

The structure of PID is also known as parallel form and is represented by,

$$G(s) = K_p + K_I\frac{1}{s} + K_D s = K_p\left(1 + \frac{1}{T_I s} + T_D s\right) \qquad (16)$$

where K_p is proportional gain, K_I is integral gain, K_D derivative gain; T_I is integral time constant and T_D is derivative time constant. The proportional term for providing an overall control action proportional to the error signal through the constant gain factor. The integral term is to reduce steady-state errors through low-frequency compensation by an integrator. The derivative term is to improve transient response through high-frequency compensation by a differentiator. The selection of gains for the PID controlees can be determined by a method developed by Ziegler and Nichols and the performance of PID controllers can be obtained by examining the integral of the absolute error.

The non linear aircraft model is complex, and the complexity arises from the uncertainty in the form of ambiguity [15]. The growth of fuzzy logic approach handles ambiguity and uncertainty existing in complex problems. Fuzzy sets represents fuzzy logic provide means to model the uncertainty associated with vagueness, imprecision and lack of information regarding aircraft dynamics. Fuzzy logic operates on the concept of membership. The membership was extended to possess various “degrees of membership” on the real continues interval between the value 0 and 1. Fuzzy sets are tools that convert the concept of fuzzy logic into algorithms [21]. Since fuzzy sets allow partial membership, they provide computer with such algorithms that extend binary logic and enable it to take human like decision. Fuzzy Logic Control (FLC) system is one of the main developments and successes of fuzzy sets and fuzzy logic. A FLC is characterized by four modules: fuzzifier; defuzzifier; inference engine and rule base. In terms of inference process there are two main types of Fuzzy Inference Systems (FIS) the Mamdani-type and the Takagi Sugeno Kang (TSK) type. In terms of use, the Mamdani FIS is more widely used, mostly because it provides reasonable results with a relatively simple structure, and also due to the intuitive and interpretable nature of the rule base [22-24].



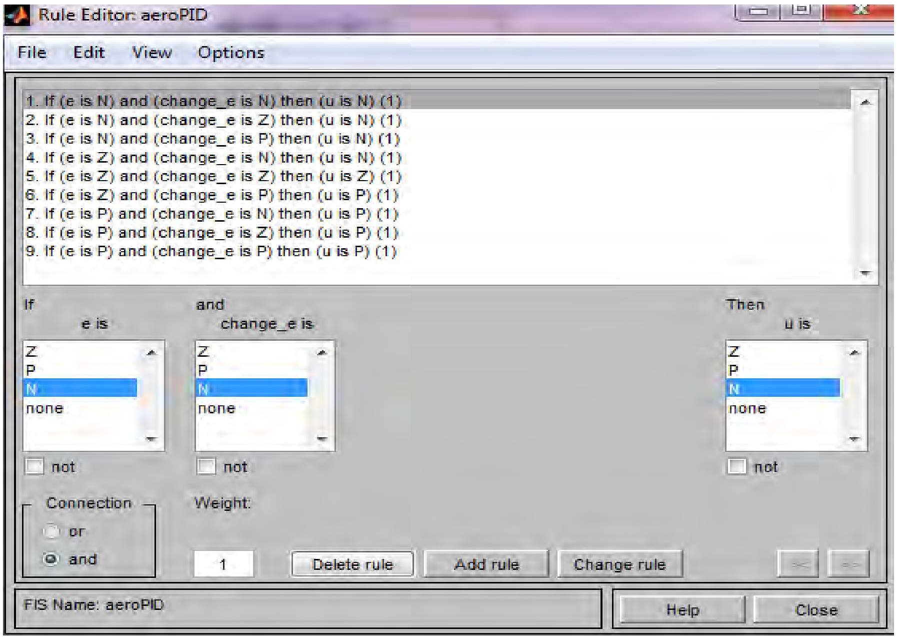
Input: [0;0]

Plot points: 101

Opened system aeroPID, 9 rules

Fig 2. Fuzzy inference in the Rule Viewer

The aircraft dynamics are highly nonlinear, trial-and-error procedures and experience play an important role in defining the rules. Each fuzzy set consists of three types of membership function, which are negative (N), zero (Z) and positive (P). Here triangular membership functions are chosen for each fuzzy set. The universe of discourse is set between -0.4 to 0.4 that implies the range of pitch angle (±0.4 radian).

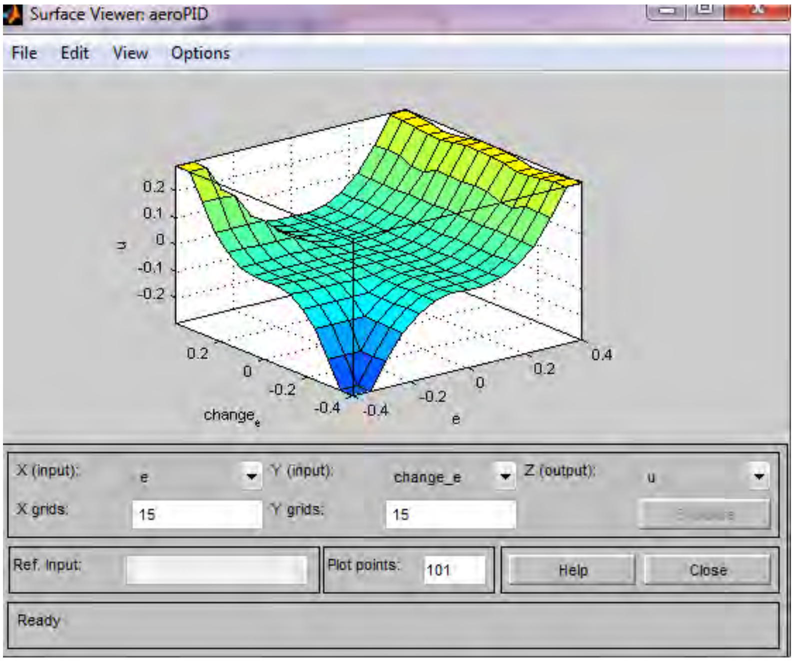

1. If (e is N) and (change_e is N) then (u is N) (1)
2. If (e is N) and (change_e is Z) then (u is N) (1)
3. If (e is N) and (change_e is P) then (u is N) (1)
4. If (e is Z) and (change_e is N) then (u is N) (1)
5. If (e is Z) and (change_e is Z) then (u is Z) (1)
6. If (e is Z) and (change_e is P) then (u is P) (1)
7. If (e is P) and (change_e is N) then (u is P) (1)
8. If (e is P) and (change_e is Z) then (u is P) (1)
9. If (e is P) and (change_e is P) then (u is P) (1)

Weight: 1

FIS Name: aeroPID

Fig 3 Fuzzy Rule Base

The appropriate membership function to represent each fuzzy set need to be defined and each fuzzy set must have the appropriate universe of discourse. Using the FIS editor, the two inputs to the fuzzy controller are the error (e) which measures the system performance and the rate at which the error changes (Δe), whereas the output of the control signal (Δu). The FIS rule is shown in figure2 and 3. The plot of output surface viewer is shown in figure 4.



X (input): e
Y (input): change_e
Z (output): u
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101
Ready

Fig 4. Three Dimensional View of Output Surface

IV. RESULTS AND DISCUSSION

The classical method, Fuzzy Controller and Hybrid Fuzzy Logic Controller response is obtained by using Matlab Simulink model. The results for Dirac's Delta impulse are given for PID and hybrid PID Controller.

A. Classical Method

The longitudinal state space matrix for aircraft dynamics as given in equation 17.

$$A = \begin{bmatrix} -63.17 & -203.14 & -776.4 & 0.0000 \\ 1.00000 & 0.0000 & 0.0000 & 0.0000 \\ 0.00000 & 1.0000 & 0.00000 & 0.000 \\ 0.0000 & 0.0000 & 1.0000 & 0.0000 \end{bmatrix} \quad (17)$$

The eigen values of the longitudinal transport is given in equation 18 and 19.

$$\lambda_{1,2} = 0,\ 60 \quad (18)$$

$$\lambda_{3,4} = -1.585 \pm i\, 3.22 \quad (19)$$

The roots are real, there is of course no period, and only parameter is the time to double or half [26]. The modes are oscillatory; it is envelope ordinate that doubles or halves. The root locus of closed loop PID controller for aircraft dynamics is shown in figure 5.

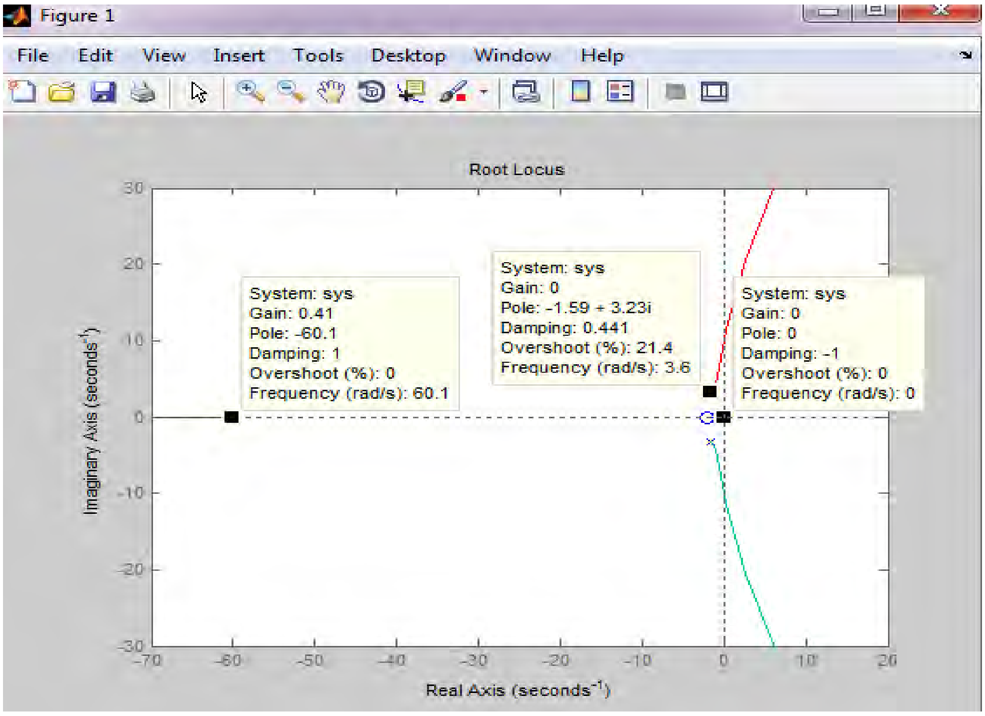


Fig 5. Root Locus of Aircraft Dynamics Response

The Dirac’s Delta impulse response of the PID controller is shown in figure 6. The delay time is 0.3secs, rise time is 0.6 secs and settling time is 18 secs. The response is oscillatory in nature.

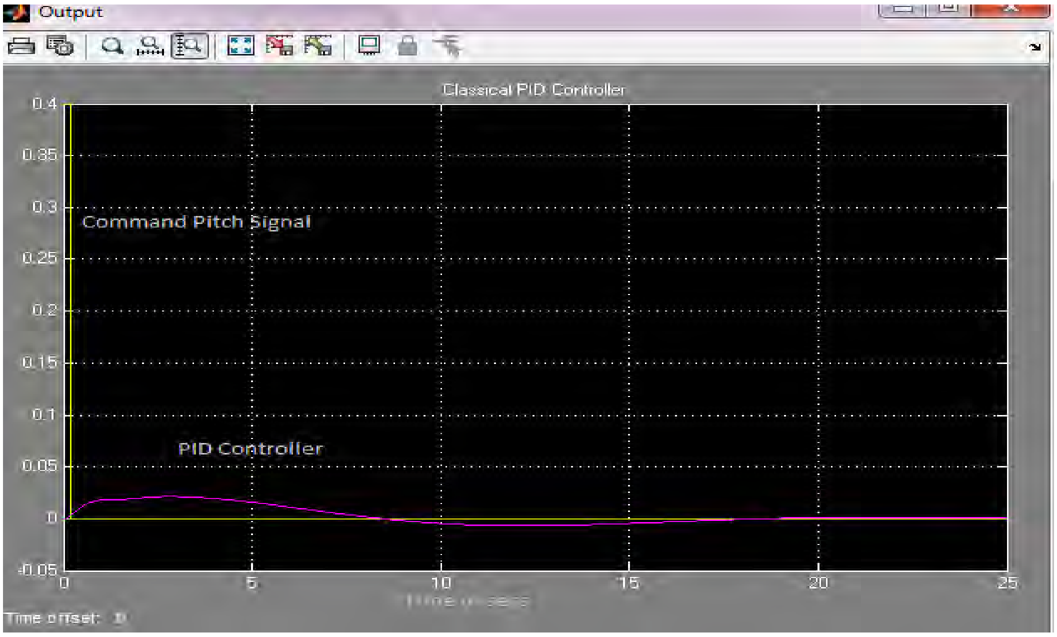


Fig 6. PID Controller Response

B Fuzzy PID Method

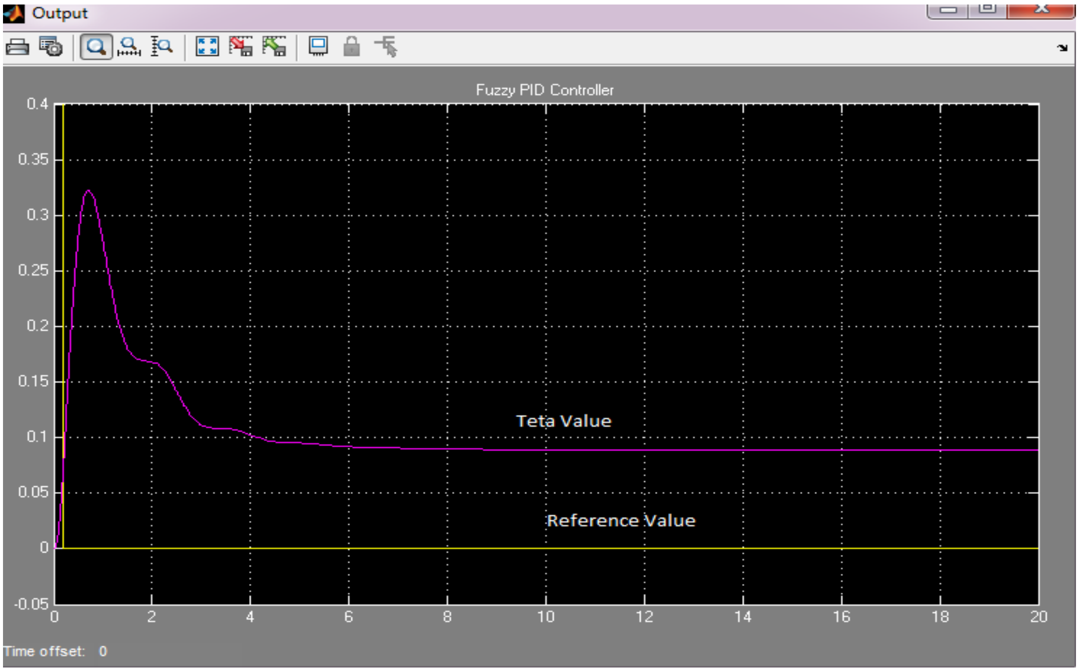


Fig 7. Fuzzy PID Controller Response

In the advanced modern aircrafts, the conventional PID (Proportional-Integral-Derivative) controllers are used extensively even though they are not very efficient for non-linear dynamic systems, mainly because of their intuitive nature, ease of operation and low cost. To overcome this flaw, an unconventional technique of Fuzzy Logic could be used as it has proven to be more efficient than PID controllers and depends on human experience and intuition [26-27]. This type of Fuzzy control was expressed by Mamdani and is very popular compared to Takagi-Sugeno type which uses fuzzy sets to define the input variables but the output is defined by means of functions or LTI systems. The Dirac's Delta impulse response of the Fuzzy based PID controller is shown in figure 7. The delay time is 0.3 secs, rise time is 0.8 secs and settling time is 6 secs. The response is smooth in nature.

C Hybrid Fuzzy PID Controller (HFPID)

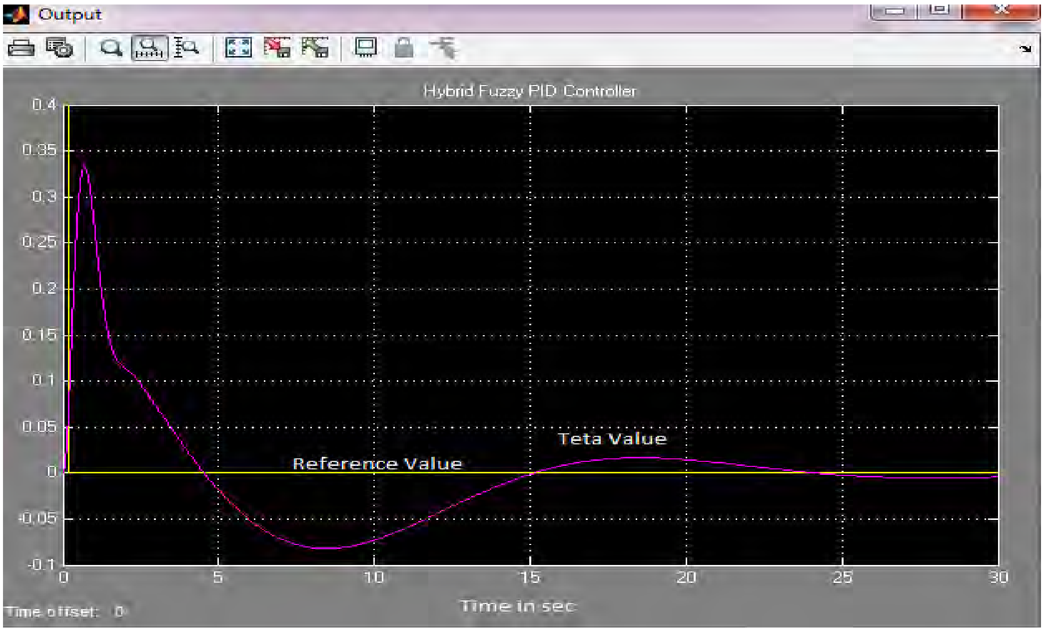


Fig 8. Hybrid Fuzzy PID Controller Response

The PID controller and Fuzzy PID controller together are called Hybrid Fuzzy PID Controller. The response of Hybrid Fuzzy PID controller is shown in figure 8. The results shown in table 1 clearly indicate Hybrid Fuzzy PID controller is the best compared to the other Controllers. The biggest advantage of the hybrid fuzzy PID controller is the robustness against noise, and its ease for implementation. There has been lot of experiments and research regarding the implementation and application of fuzzy logic in flight control systems from Unmanned Aerial Vehicle (UAV) to fighter jets. The combined response of controllers is shown in figure 9.

TABLE I COMPARISON OF PID, FUZZY CONTROLLER AND HFPID CONTROLLER

	PID Controller	**Fuzzy Controller**	**HFPID Controller**
Delay Time T_d in secs	0.3	0.4	0.3
Rise Time T_r in secs	0.6	0.8	0.75
Settling Time T_s in sec	18	6	24
% Steady State Error E_{ss}	0	8%	0

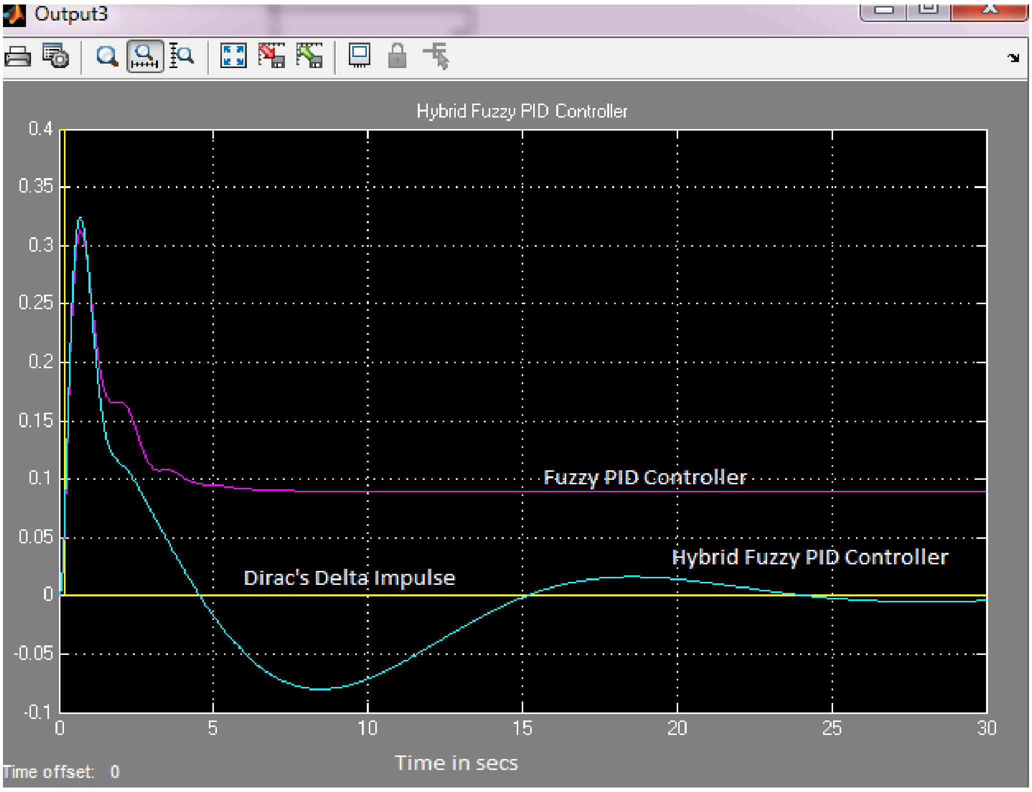


Fig 9 Combined Controller Responses

V. CONCLUSION

In this paper, fuzzy logic based intelligent controller design is given for controlling non linear longitudinal pitch control of an aircraft. Although, there have been many developed techniques to control a dynamic system using feedback as PID control, but very few control techniques are actually implemented in the real world flight control applications. The main reason behind not implementing the advanced optimal control techniques is that they are not intuitive and in aerospace where safety is a high priority, unintuitive techniques are not trusted enough to be implemented in real aircrafts. The Hybrid Fuzzy PID controller can effectively eliminate these dangerous oscillations and provides smooth operation in transient period. Also it is giving a steady state error of 8%, which is a considerable value. The fuzzy control works very efficiently for nonlinear dynamic systems and it’s simple and intuitive which is precisely what is required in the current and future aerospace industry.

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