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Performance Analysis of Aircraft Pitch Control By Linear Quadratic Regulator and Fuzzy Controller

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Abstract: ***Today's aircraft consist of number of automatic controller that helps the airplane crew in airplane management and piloting the aircraft. Usually, the control strategies of aircraft can be grouped into two categories as follows: lateral and longitudinal control. In longitudinal control, the pitch angle has been employed for an aircraft system. Pitch of an aircraft may be described as a rotation around the lateral axis. An elevator is used to control pitch of aircraft which is located at the back of an airplane. So in this paper, a pitch control of an aircraft has been implemented by using Fuzzy controller. The stability of aircraft system is of major concern in real interface system. Thus, aircraft system must be accurate having stable response of aircraft system and should approaches to reference over a certain interval of time i.e. it should not oscillate over a long time. So this work exhibits the design of fuzzy control strategy for controlling the pitch angle of an aircraft. Two control strategies: Linear quadratic regulator (LQR) control and Fuzzy control strategies have been employed and compared. After that a comparative analysis of these control strategies has been done. The whole system has been implemented in MATLAB SIMULINK environment.***

Keywords: Pitch control, longitudinal l control, Lateral control, Fuzzy controller, linear quadratic regulator (LQR).

I. INTRODUCTION

Pitch control is a longitudinal control; therefore longitudinal model of an aircraft is used to design the pitch angle controller of an aircraft. Roll control is a lateral control. Therefore lateral model of an aircraft is required to design the roll angle controller of an aircraft. The roll angle is used to control the rolling motion of an aircraft. Elevator is used to control pitch of an aircraft and ailerons are used to control roll of an aircraft. The ultimate aim is to follow the elevator and ailerons command with minimum delay and maximum accuracy. To reduce the complexity of system, assume aircraft as a rigid body and aircraft's motion consist of a small deviation from its equilibrium flight condition [1]. In addition, the aircraft control system can be divided into two parts, namely longitudinal and lateral control [2]. In longitudinal control, the elevator controls pitch or the longitudinal motion of aircraft system whereas in lateral control lateral motion (roll and yaw) of aircraft system is controlled. Pitch of an aircraft may be described as a rotation around the lateral axis. It might be calculated as the angle between the direction of speed in a horizontal line and vertical plane 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 [3]. Elevator is used to control pitch or to control the tail planes of an aircraft which is located at the back of an airplane. The elevator pivoted at the rear of an aircraft work in pairs; when the right elevator goes up, the left elevator also goes up. The linear zed mathematical model is of third order. Pitch control is a longitudinal problem, and this work presents on design a controller that controls the pitch of an aircraft [4-5]. Lot of research work 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].

This work presents investigation into the development of pitch control scheme by controlling the pitch angle of an aircraft system. A modern controller (LQR) and Fuzzy Controller are developed to control the pitch of an aircraft system. Simulation has been developed in the MATLAB Simulink for evaluation of the both control strategies. Performance of both control strategy with respect to the pitch angle and pitch rate is examined. Comparison of both control schemes to the system performance of aircraft system is presented and discussed.

II. MATHEMATICAL MODEL FOR 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 modeling of pitch control longitudinal equation of aircraft, as a basis of a simulation environment for development and performance evaluation of the proposed controller technique [8-9].

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The pitch control system considered in this work is shown in Fig. 1 where X_b, Y_b and Z_b represent the aerodynamics force components. θ, Φ and δ_e represent the orientation of aircraft (pitch angle), orientation of aircraft (roll angle) and elevator deflection angle in the earth-axis system respectively.

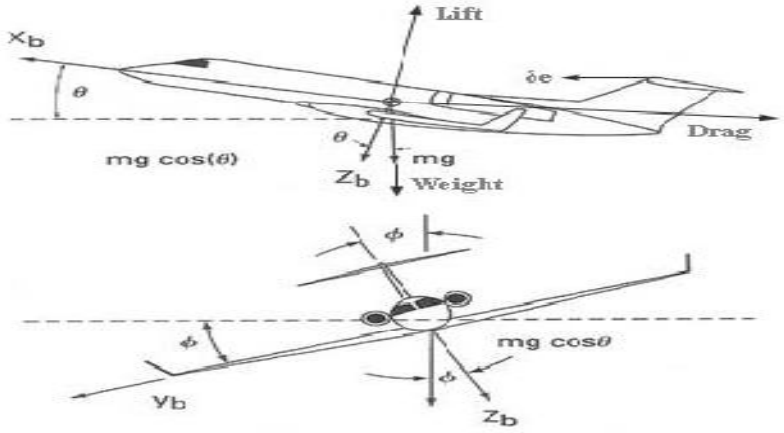

Fig1. Description of pitch control system.

The forces, moments and velocity components in the body fixed coordinate of aircraft system can be described as shown in Fig. 2. The aerodynamics moment components for roll, pitch and yaw axis are represented 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 represents the angle of attack and sideslip respectively. In this study the data from General Aviation Airplane [1-2] is used in system analysis and modeling.

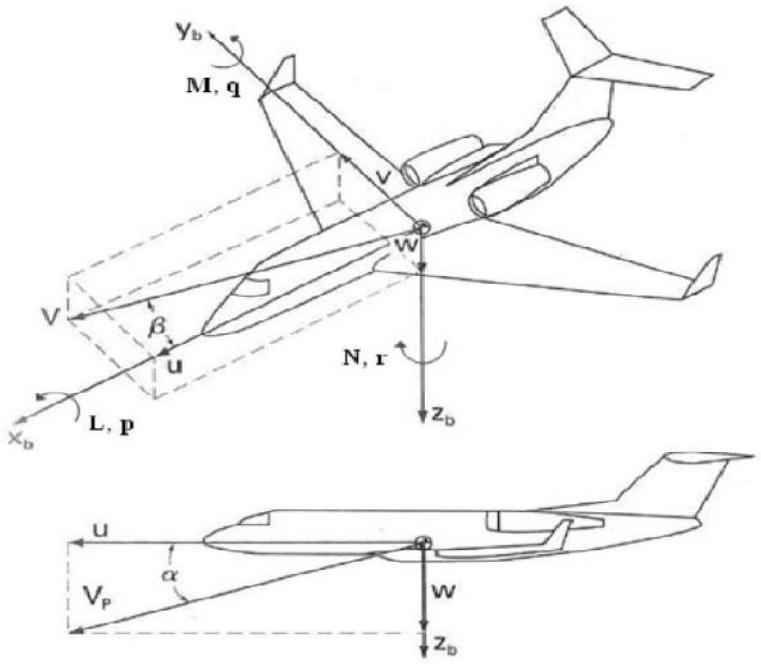

Fig2. Definition of force, moments and velocity in body fixed coordinate.

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 Fig. 1 and Fig. 2, the following dynamic equations include force and moment equations are determined as shown in (1), (2) and (3). By referring to the Fig. 1 and Fig. 2, the following dynamic equations include force and moment equations are determined.

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

$$Z + mgC_\phi = m(\dot{w} + pv - qu) \quad (2)$$

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

Certain assumptions need to consider solving the aircraft problem:

Pitch angle ; $\dot{\theta} = qC_\phi - rS_\phi$

Piching rate ; $r = \dot{\phi}C_\theta - \dot{\theta}S_\varphi$

Roll angle ; $\dot{\phi} = p + qS_\phi T_\theta + rC_\phi T_\theta$

Rolling rate ; $p = \dot{\emptyset} - \dot{\phi}S_\theta$

aw angle ; $\dot{\phi} = (qS_\phi - rC_\phi)\sec\theta$

Yawing rate ; $q = \dot{\theta}C_\phi + \dot{\phi}C_\theta S_\phi$

Table1 Longitudinal Stability Derivative Parameters

Longitudinal Derivatives	Dynamics Pressure and Dimensional Derivative Components Q = 36.8lb/ft2, QS = 6771lb, QS$\bar{c}$=38596ft.lb, $\bar{c}/2u_0$ = 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	$X_w = 0.03$	$Z_W = -2.02$ $Z_{\dot{w}} = 0$	$M_w = 0.05$ $M_{\dot{w}} = 0.051$
Angle of attack	$X_\alpha = 0$ $X_{\dot{\alpha}} = 0$	$Z_\alpha = -355.42$ $Z_{\dot{\alpha}} = 0$	$M_\alpha = -8.8$ $M_{\dot{\alpha}} = -0.8976$
Pitching rate	$X_q = 0$	$Z_q = 0$	$M_q = -2.05$
Elevator Deflection	$X_{\delta e} = 0$	$Z_{\delta e} = -28.15$	$M_{\delta e} = -28.15$

Equations (1), (2) and (3) should be linearized using small disturbance theory and the variables are replaced as given in (4) by introducing the small perturbation or disturbance.

$$u = u_0 + \Delta u \qquad v = v_0 + \Delta v \qquad w = w_0 + \Delta w$$

$$p = p_0 + \Delta p \qquad q = q_0 + \Delta q \qquad r = r_0 + \Delta r$$

$$X = X_0 + \Delta X \qquad M = M_0 + \Delta M \qquad u = u_0 + \Delta u$$

$$\delta = \delta_0 + \Delta\delta \quad (4)$$

For simplicity certain assumptions are taken. First, the reference aircraft conditions are considered to be symmetric and second, the propulsive forces are considered to be same throughout the flight i.e. $p_0 = v_0 = r_0 = q_0 = w_0 = \varphi_0 = 0$. After linearization of equations (5), (6), and (7) these are obtained as follows:

$$\left(\frac{d}{dt} - X_u\right)\Delta u - X_w\Delta w + (g\cos\theta_0)\Delta\theta = X\delta_e\Delta\delta_e \quad (5)$$

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$$-Z_u\Delta u + \left[(1 - Z_w)\frac{d}{dt} - Z_w\right]\Delta w - \left[(u_0 - Z_q)\frac{d}{dt} - g\theta_0\right]\Delta\theta = Z_{\delta_e}\Delta\delta_e \quad (6)$$

$$-M_u\Delta u + \left(M_w\frac{d}{dt} - M_w\right)\Delta w - \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta = M_{\delta_e}\Delta\delta_e \quad (7)$$

Where $X_u = \partial X/\partial u/m$, $X_w = \partial X/\partial w/m$ etc. are aerodynamic derivatives divided by the airplane mass. By solving the (5), (6), (7) and putting the longitudinal stability derivatives parameter values from Table I, the transfer function for $\Delta q(s)$ to $\Delta\delta_e(s)$ is shown as obtained in (8), where $\Delta q(s)$ represent the variation in pitch rate and $\Delta\delta_e(s)$ represent the variation in elevation rate for pitch control system of an aircraft.

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-\left(M_{\delta_e} + \frac{M_{\dot\alpha}Z_{\delta_e}}{u_0}\right)s - \left(\frac{M_\alpha Z_{\delta_e}}{u_0} - \frac{M_{\delta_e}Z_\alpha}{u_0}\right)}{s^2 - \left(M_q + M_{\dot\alpha} + \frac{Z_\alpha}{u_0}\right) + \left(\frac{Z_\alpha M_q}{u_0} - M_\alpha\right)} \quad (8)$$

The transfer function of variation in pitch angle to the variation in elevator angle can be obtained from the (8) as under.

$$\Delta q = \Delta\dot\theta \quad (9)$$

$$\Delta q(s) = s\Delta\theta(s) \quad (10)$$

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s} * \frac{\Delta q(s)}{\Delta\theta(s)} \quad (11)$$

Thus the transfer function for the aircraft pitch control system is obtained in (12) and (13).

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s} * \frac{-\left(M_{\delta_e} + \frac{M_{\dot\alpha}Z_{\delta_e}}{u_0}\right)s - \left(\frac{M_\alpha Z_{\delta_e}}{u_0} - \frac{M_{\delta_e}Z_\alpha}{u_0}\right)}{s^2 - \left(M_q + M_{\dot\alpha} + \frac{Z_\alpha}{u_0}\right) + \left(\frac{Z_\alpha M_q}{u_0} - M_\alpha\right)} \quad (12)$$

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{11.7304s + 22.578}{s^3 + 4.9676s^2 + 12.941s} \quad (13)$$

The transfer function can also be represented in state space form as obtained in (14) and (15).

$$\begin{bmatrix}\Delta\dot\alpha\\ \Delta\dot q\\ \Delta\dot\theta\end{bmatrix} = \begin{bmatrix}-2.02 & 1 & 0\\ -6.9868 & -2.9476 & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\Delta\alpha\\ \Delta q\\ \Delta\theta\end{bmatrix} + \begin{bmatrix}0.16\\ 11.7304\\ 0\end{bmatrix}[\Delta\delta_e] \quad (14)$$

$$y = [0 \quad 0 \quad 1]\begin{bmatrix}\Delta\alpha\\ \Delta q\\ \Delta\theta\end{bmatrix} + [0] \quad (15)$$

In the above equations, a Mathematical modeling of Aircraft pitch control system is presented which helps to understand the aircraft system so as to further investigation.

A. *Control Methodology*

In this section, two control schemes are proposed and described in detail which is Linear Quadratic Regulator (LQR) and Fuzzy Control Scheme. Furthermore, a few of design specification have to be set to investigate the performance of both control strategies. In this work, four considerations have to be met which are rising time less than 3 second, settling time less than 5 second, percentage of overshot less than 10% and steady state error less than 2% for controlling the pitch angle of 0.2 radian (11.5 degree).

B. *LQR Controller*

Linear-quadratic-regulator (LQR) is a part of optimal control strategy which has been widely developed and used in various applications [10]. LQR design is based on the selection of feedback gains K such that the cost function J is minimized. This ensures that the gain selection is optimal for the cost function specified. The performance index J is defined

$$J = \int_0^\infty (x^T Qx + u^T Ru)\,dt \quad (16)$$

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Where 'Q' and 'R' are gain matrices which must be positive semi definite. It is a methodology in modern control system that optimizes the value of performance index J. It uses the feedback control strategy to analyze a system. The system can be stabilized by choosing the proper value of feedback gain K. The feedback control law that minimizes the value of the cost is given by

$$u = -Kx \quad (17)$$

Where K is given by

$$K = -R^{-1}B^{T}P \quad (18)$$

And the value of P is computed by solving the continuous time algebraic Riccati equation (ARE).

$$A^{T}P + PA - PBR^{-1}B^{T}P + Q = 0 \quad (19)$$

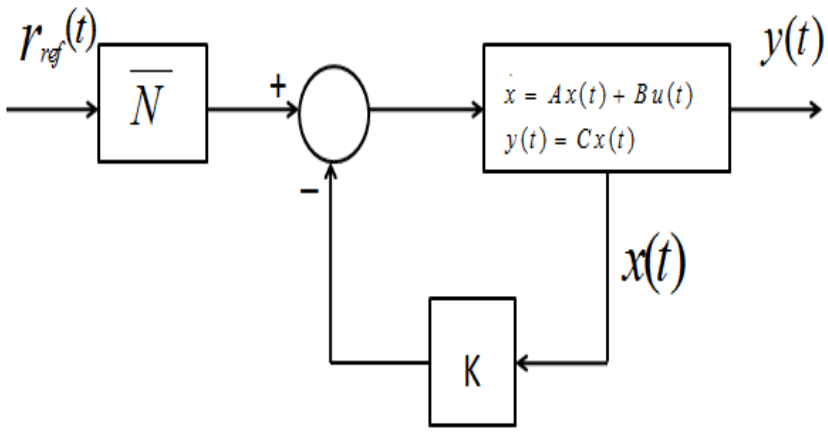

Fig. 3 Full-state feedback controller with reference input.

Pre compensation is used to reduce the steady state error $e(t)$ of the output $y(t)$. Pre compensated gain $\bar{N}$can be used after the input$r_{ref}(t)$. Value of gain $\bar{N}$can be computed using the MATLAB user defined function.Design of LQR controller, it is required to calculate the value of the gain K. it is calculated using algebraic Riccati equation (ARE) by choosing appropriate values of Q and R. The controller can be tuned by varying the value of Q and R matrix by varying matrix to get the desired performance characteristics as shown in fig.3.

C. Fuzzy Logic Controller

In this work, fuzzy logic controller has been applied for stabilization of the pitch control system. FLC is conceived as a better method for sorting and handling data but has proven to be an excellent choice for many control system applications because of non-linearity, complex mathematical computation and real-time computation need. It can be built into anything from small, hand-held products to large computerized process control systems. It uses an imprecise but very descriptive language to deal with input data more like a human operator [11]. It is very robust and forgiving of operator and data input and often works when first implemented with little or no tuning. Based on these properties, fuzzy logic controller plays the best to fit the requirements in such cases. FLC incorporates a simple rule-based "If X and Y then Z" approach to solving control problem rather than attempting to model a system mathematically. The fig. 4 shows the overall closed-loop system for FLC with the pitch control of an aircraft. The 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 is the change of the control signal (Δu). From the Fig. 4, the error (e) is computed by comparing the reference point (desired angle) with the plant output. The change of error (Δe) is generated by the derivation of the error. The error and change of error is fed to the fuzzy controller through a multiplexer.

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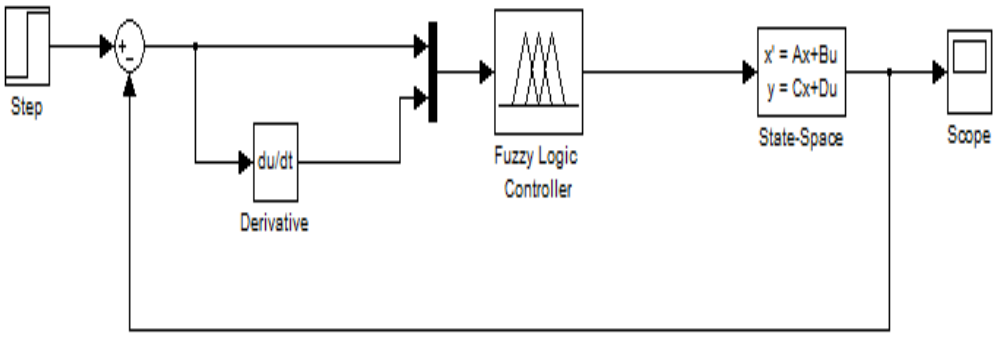

Fig.4 Fuzzy logic controller in feedback loop of pitch control system.

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 FLC, the standard fuzzy rules generated from the under damped response curve. This response is transform into fuzzy rules using the formula obtained below.

$$e(k) = r(k) - y(k)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (20)$$

In this work, the triangular membership function is chosen for each fuzzy set. The universe of discourse is set between -15 to 15 and -12 to 12 that implies the range of pitch angle and pitch rate respectively. A two input, one output fuzzy 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 [11]. These are nine rules that have been utilized in designing the controller and the rule is defined in Table 2.

Table 2 Rules for the fuzzy controller

Rules	Error, e	Delta error ,de	Delta u, du
1	N	N	N
2	N	Z	N
3	N	P	N
4	Z	N	N
5	Z	Z	Z
6	Z	P	P
7	P	N	P
8	P	Z	P
9	P	P	P

Since there are a total of three fuzzy variables (two inputs and one output), and each fuzzy variable has three membership functions, the fuzzy controller for pitch control of an aircraft has a total of nine membership functions. Each membership function is constrained to be triangular so each membership function has three parameters (a modal point and two half width). Nine rules have been obtained with the combination of two input variables and one output variables having three membership functions as shown in fig5 to fig7.

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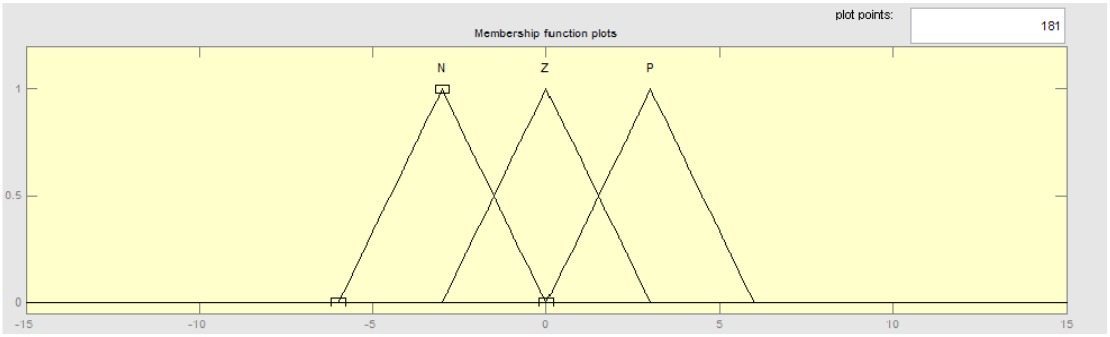

Fig.5 Fuzz set of input (I)

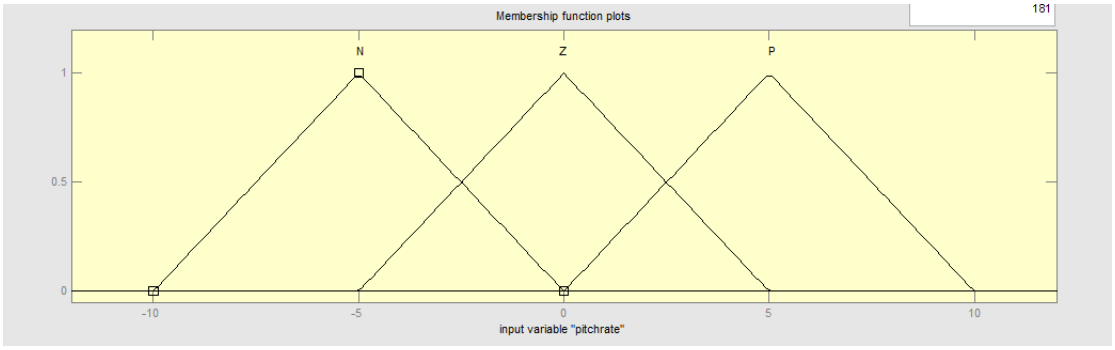

Fig.6 Fuzzy set of input (II)

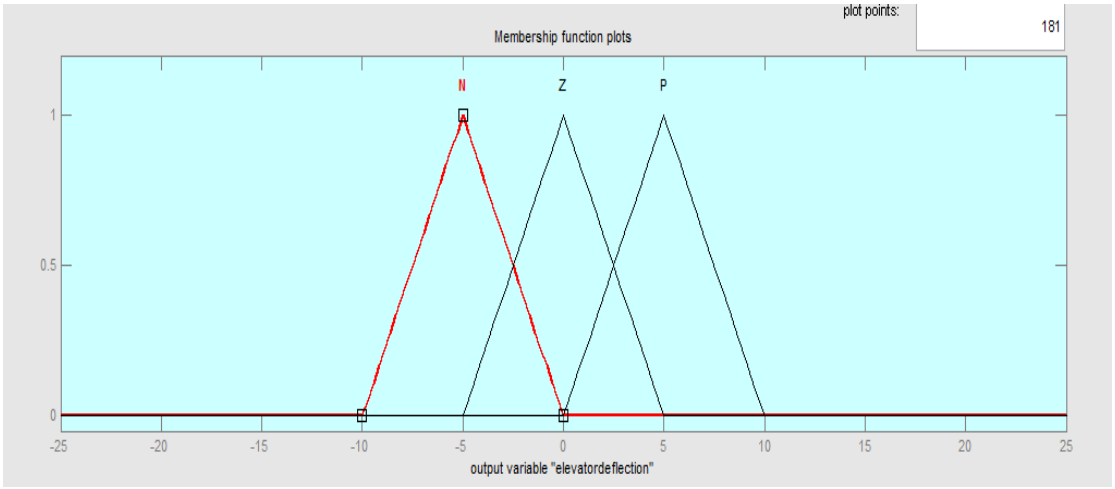

Fig.7 Fuzzy set of output

In this, a unit step command is required in order for pitch angle to follow the reference value of 0.2 radian = 11.5 degree. Two inputs have been applied to fuzzy logic controller which is the error (e) that computed by comparing the reference point (desired angle) with the plant output and the change of error (Δe) which generated by the derivation of the error. The fuzzy logic controller provides good performance in term of percent overshoot that is 0%. This controller is able to give a good response without produce any overshoot.

III. RESULTS AND DISCUSSION

Here, certain characteristics are required to be met for controlling the pitch angle response of reference size equals 0.2 Radian or 11.5 degree as shown in Table 3.

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Table 3 Desired performance specifications

Response Characteristics	Pitch angle response
Rising time(T_r)	1 s
Settling time(T_s)	0.2 s
Percentage overshoot (%Os)	5%
Steady state error (e_{ss}%)	2 %
Disturbance rejection (T_d)	2s

Design of LQR controller, it is required to calculate the value of the gain K. It is calculated using Riccati equation by choosing appropriate values of Q and R. The controller can be tuned by varying the value of x in Q matrix. The performance characteristics for different values of Q and R are shown in Table 4and Table 5 respectively.

$$= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \end{bmatrix} \qquad (21)$$

R= [r] (22)

As a result, by choosing the different values of x in matrix Q the pitch angle responses are obtained as shown in Fig. 8.The response characteristics for different values of x in Q are shown in Table 4. The response of pitch angle response may improve even more by increasing the value of x in Q.The controller can also be tuned by varying the value of R matrix.

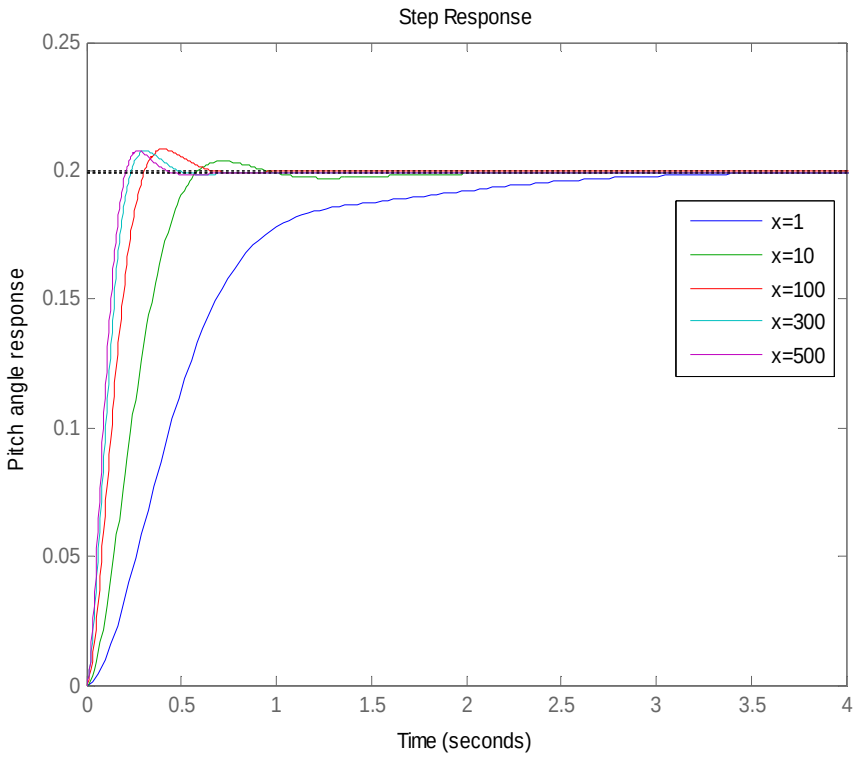

Fig.8 Pitch angle response with LQR for different values of x

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Table 4 Response Characteristics of LQR controller with different values of x

Response characteristics	Pitch Angle Control				
	x=1	x=10	x=100	x=300	x=500
Rising time( )	1.2s	0.36s	0.2s	0.15s	0.132s
Settling time( )	2.9s	1s	0.435s	0.414s	0.366s
Percentage overshoot (%)	0	2.24	4.18	4.32	4.35
Steady state error (e_{ss}%)	0.1	0.01	0.01	0.01	0.01

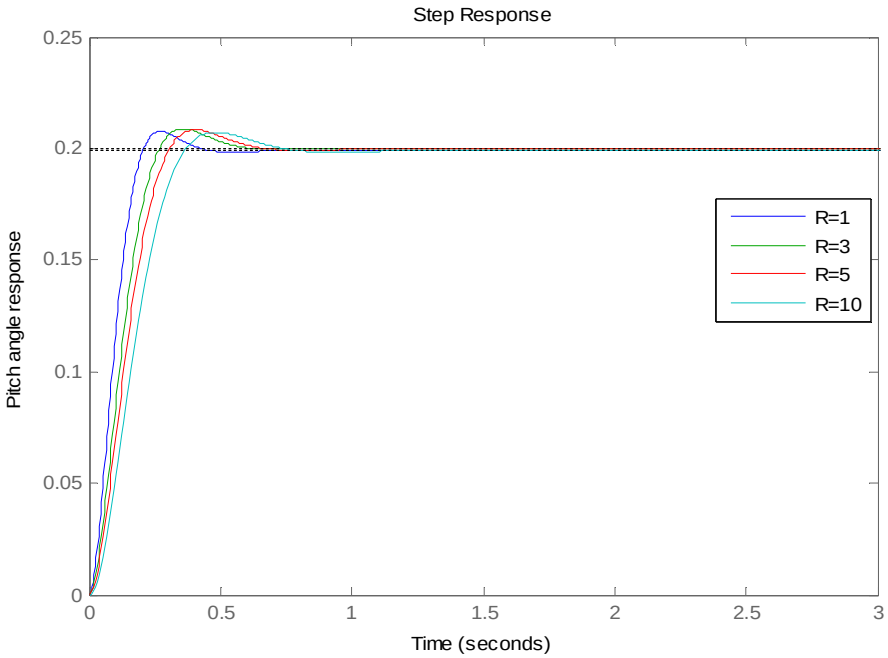

Fig. 9 Pitch angle response with LQR for different values of R

As a result, by choosing the different values R the pitch angle responses are obtained as shown in Fig. 9 and the performance characteristics for different values R are shown in Table 5.

Table 5 Response Characteristics of LQR controller with different values of R

Response characteristics	Pitch Angle Control			
	R=1	R=3	R=5	R=10
Rising time( )	0.132s	0.174s	0.198s	0.235s
Settling time( )	0.366s	0.476s	0.535	0.622
Percentage overshoot (%)	4.35	4.27	4.18	3.94
Steady state error (%)	0.01	0.01	0.01	0.01

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The fig.10 shows the pitch angle response with fuzzy logic controller. Two inputs have been applied to fuzzy logic controller which is the error (e) that computed by comparing the reference point (desired angle) with the plant output and the change of error (Δe) which generated by the derivation of the error. The fuzzy logic controller provides good performance in term of percent overshoot that is 0%.

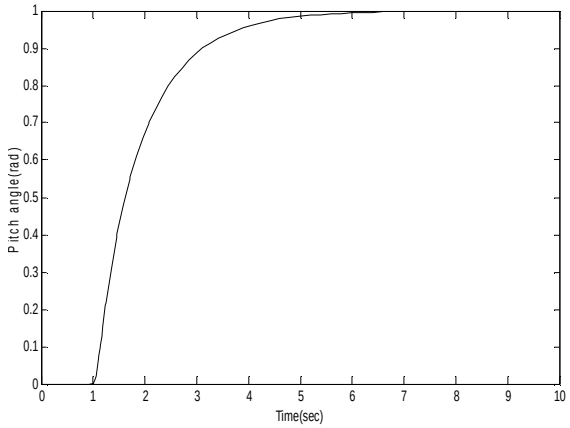

Fig.10 Pitch angle response with fuzzy control

Table 6 Response Characteristics of Fuzzy Controller

Response Characteristics	Pitch angle response
Rising time( )	1.984s
Settling time( )	4.232s
Percentage overshoot (%)	0%
Steady state error (%)	0.6452

Fig. 11 shows the 3D surface generated as a function of fuzzy set theory which summarizes the rules system. This 3D surface shows the stability of fuzzy controller and satisfied the result evaluated in odd circumstances. The 3D surface in Fig. 11 clearly represents that when two input values are low, the output is also low. The output is gradually increasing in correspondence with the changes in inputs. And an abrupt rise can also be seen when input values are very high.

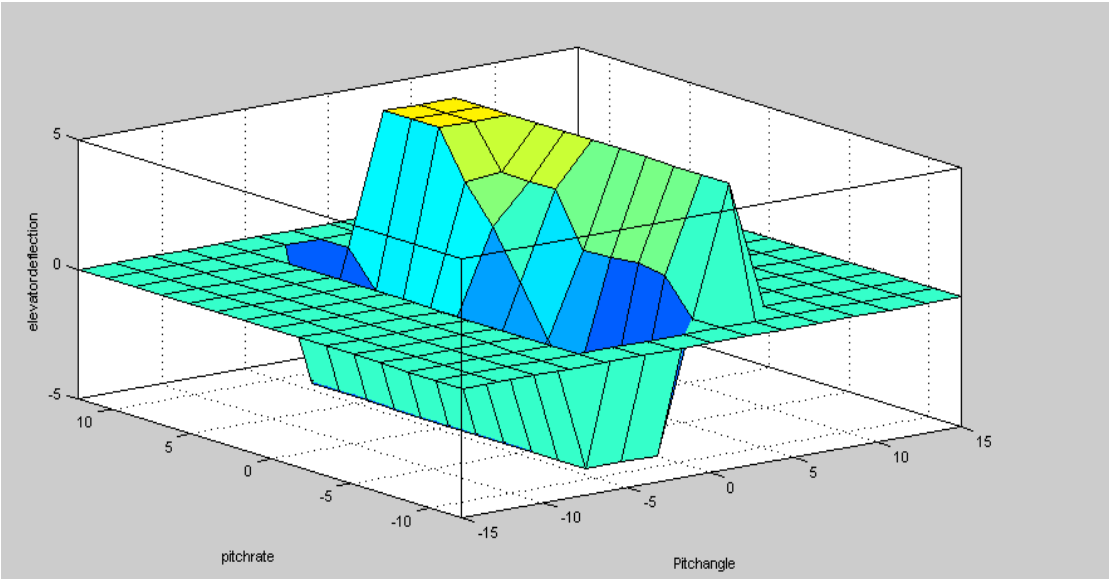

Fig. 11 Surface Generationin Fuzzy system

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Overall the complete system is minimizing and maximizing in coherence with the input and output values, so it can be summarized that the system is completely balanced and stable. It becomes necessary to evaluate the defuzzyfied results before reaching the final conclusion. Here the Defuzzification has been done, as a deciding element for an appropriate representative value in the final output to find the conclusion. Using his analysis and the obtained defuzzyfied output in Fig. 12, it is possible to obtain results for different combination of independent variables.

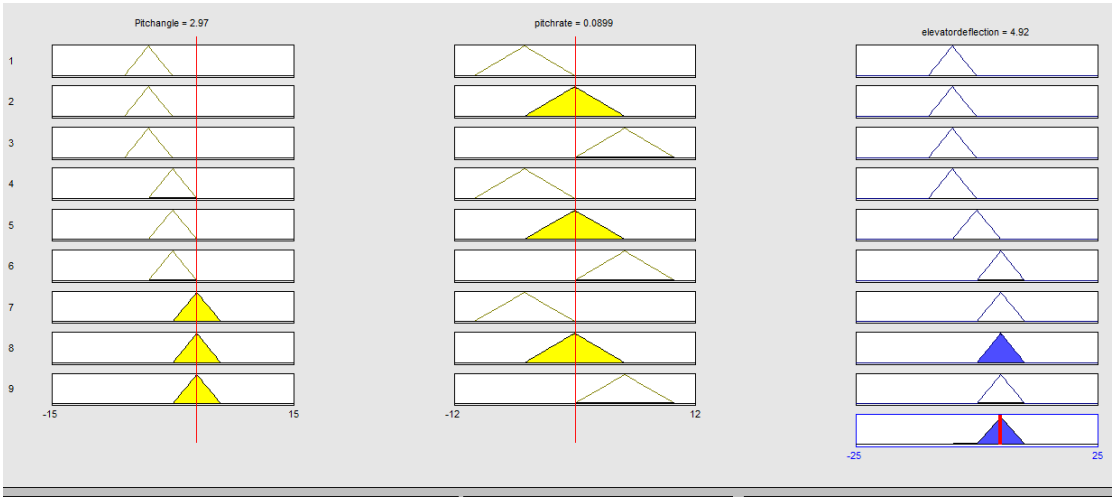

Fig.12 Defuzzyfied Output

The performance characteristics of the step response for the pitch angle between LQR and Fuzzy logic controllersare shown in Table 7.

Table 7 Performance characteristic of pitch angle

Response Characteristics	Pitch angle	
	LQR (x=100)	Fuzzy Controller
Rising time( )	0.198 Sec	1.984 Sec
Settling time( )	0.535 Sec	4.232 Sec
Percentage overshoot (%)	4.180	0.000
Steady state error (%)	0.200	0.6452

The LQR and Fuzzy Control strategies are designed successfully. As the performance of these controllers are widely dependent upon the choice of its free parameters such as Q and R matrices for LQR controller. Hence, at last fuzzy controller gives 0% Os, when compared to LQR.

IV. CONCLUSION

The pitch controller of an aircraft is required to stabilize the pitch angle at it desired value. From the comparative analysis of their performance characteristics of the these two controllers for longitudinal pitch angle control of aircraft system it is clear that the Fuzzy Logic Controller gives 0% overshoot as compare to LQR. The LQR controller has better performance as compared to fuzzy logic controller in terms of Rising Time and Settling Time. The LQR controller provides higher ability in controlling the pitch angle as compared to fuzzy logic controller in terms of Rising and Settling time except percentage peak overshoot. Therefore, Both LQR controller and Fuzzy Logic controller are cable to control the pitch angle of the aircraft system.

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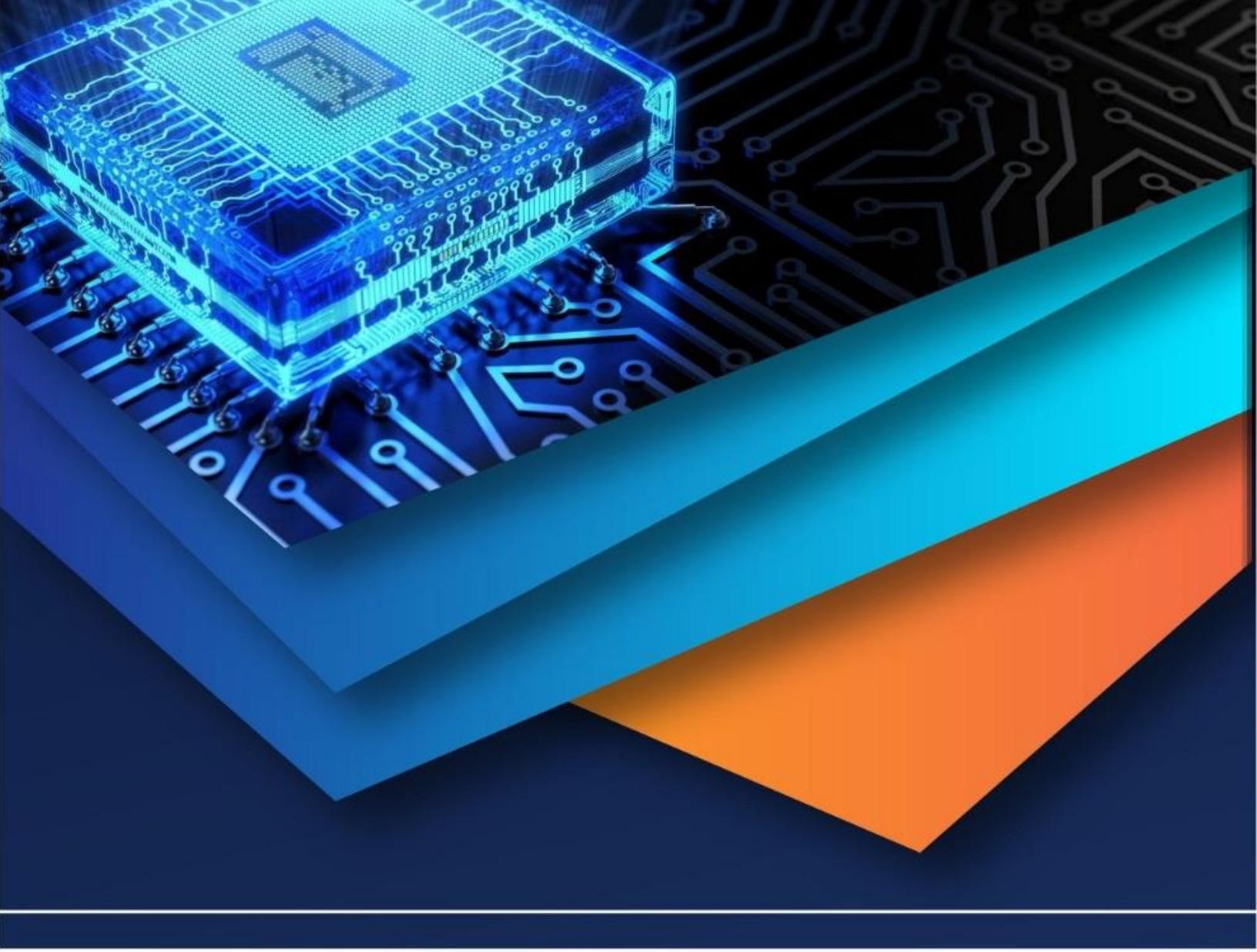

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