Volume-7, Issue-3, May-June 2017
International Journal of Engineering and Management Research
Page Number: 399-405

QFT Robust Controller Design for Aircraft Pitch Control

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ABSTRACT

Parametric uncertainty is the one of the challenging task in many dynamical systems. In this paper QFT based PID Controller is developed to improve the performance for a pitch control of uncertain aircraft system. The controller is designed based on the dynamic modeling of system begins with a derivation of suitable mathematical model to describe the longitudinal motion of an aircraft. Genetic Algorithm based QFT tuning mechanism is used to tune PID controller by selecting appropriate bounds and tracking specifications. A Comparative assessment based on time response specifications between Self-tuning fuzzy PID Controller, QFT Controller and GA based QFT Controller for an autopilot of longitudinal dynamic in pitch aircraft is investigated and analyzed.

***Keywords*--** pitch; flight control; PID; self-tuning fuzzy PID; QFT, GA based QFT

I. INTRODUCTION

Aircraft and missiles are usually equipped with a control system to provide stability, disturbances rejection and reference signal tracking. The motion of an aircraft in free flight is extremely complicated [1]. Generally, aircraft contains three translation motion (vertical, horizontal, transverse) and three rotational motion (pitch, yaw and roll) by controlling aileron, rudder and elevator. To reduce the complexity of analysis, the aircraft is assumed as a rigid body and aircraft's motion consist of a small deviation from its equilibrium flight condition [2]. In addition, the control system of aircraft can be divided into two groups, namely 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 rare of the airplane running parallel to the wing that houses the ailerons. Pitch control is a longitudinal problem, and this work presents on design of an autopilot that controls the pitch of an aircraft .autopilot is a pilot relif mechanism that assists in maintaining an attitude, heading altitude or flying to navigation or landing reference [3].

The combination of non-linear dynamics, modeling uncertainties and parameter variation in characterizing an aircraft and its operating environment are the one major problem of flight control system. This work is attempted to study the control strategies required to address the complex longitudinal dynamic characteristics of such aircraft. Many research works has been done in [4], [5], [6], [7] and [8], to control pitch or longitudinal dynamics of an aircraft for the purpose of flight stability. This research still remains an open issue in the present and future works.

Tools of computational intelligent such as fuzzy logic controller have been use in various applications including in the pitch control and it is convenient to implement in complex process, Several previous works on improving fuzzy logic controller can be found in [9]. Vick and Cohen [8] 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 [6] the synthesis of different fight controllers are developed on two hybrid intelligent control systems combining computational intelligence methodologies with other control techniques for altitude control of aircraft. For the conventional controller design ZN method is used. QFT is a unified frequency domain technique utilizing the Nichols chart (NC) for achieving the desired robust design over a specified region of plant uncertainty. This method was created and developed by Horowitz (1963). It is now recognized as a well-established method for the design of robust controllers for the plant with large classes of uncertainties, output/input disturbances, and noises. This method was successfully implemented in process control(Nataraj, 1992), fight control(Breslin&Grimble, 1997 ; Pachter, Houpis & trosen, 1997), ,marine control(satpati& sadhu, 2008; satpati, Bandyopadhyay, Koley, & Ojha,2008), missile control(Benshabat & Chait, 1993), power systems(Satpati, Bandyopadhya, Das, & Koley, 2008; ShrikantRao & Sen, 1999) and power electronics applications(Altowati, Zenger, & Suntio,2007), robot manipulator control(Farsi, 1993) [12].

This work presents investigation into the development of pitch control schemes for pitch angle of an aircraft by using Self-tuning fuzzy PID Controller, QFT Controller and GA based QFT Controller. Simulation studies are developed with the help of MATLAB for evaluation of control strategies. To demonstrate the effectiveness of the purposed control schemes, the comparative assessment on the system performance for each controller is presented and discussed.

II. MODELING OF A PITCH CONTROL

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 evaluation of the performance of proposed controller techniques. To reduce the complexity of analysis, the equation governing motion of an aircraft can be separated into two groups namely the longitudinal and lateral equations. 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 δe represent the orientation of aircraft (pitch angle) in the earth–axis system and elevator deflection angle.

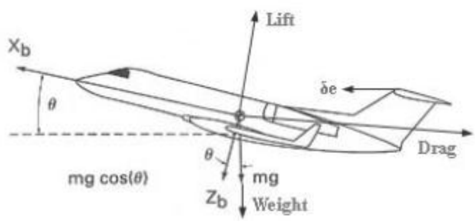

Fig.1. Description of pitch control system

Fig. 2 shows the force moments and velocity components in the body fixe 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 represents the angle of attack and sideslip. In this study the data from general aviation airplane [1] is used in system analysis and modeling.

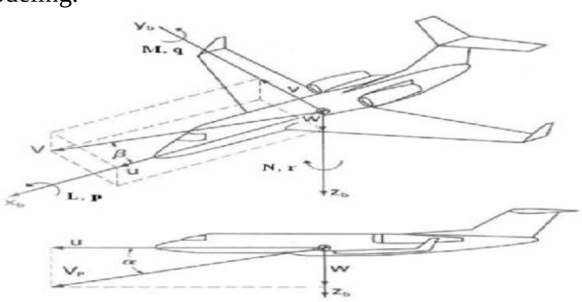

Fig.2. Definition of force, moments and velocity in body fixed coordinate

The longitudinal stability parameters [1] are denoted in table I. The parametric uncertainty considered for all the parameters is ±20% to the nominal parameters.

Table - I. Longitudinal Stability Derivative Parameters with Nominal Values

Longitudinal derivatives	Components		
	Dynamic pressure and dimensional derivative Q=36.8lb/ft^2,QS=6771lb, $QS\bar{C}$=38596$ft.lb$,($\bar{c}/2u_0$)=0.016s		
	X-Force(s^{-1})	Z-Force(Z^{-1})	Pitching Moment(FT^{-1})
Rolling velocities	X_u=-0.045	$Z_{u=}$-0.369	M_u=0
Yawing velocities	X_w=0.036 X_w=0	Z_w=-2.02 Z_w=0	M_w=-0.05 M_w=-0.051
Angle of attack	X_α=0 X_α=0	Z_α=-355.42 Z_α=0	M_α=-8.8 M_α=-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

A few assumptions 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.

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

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

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

It is required to completely solve the aircraft problem with considering the following assumptions:

a. Rolling rate, $p=\dot{\Phi}-\Psi S_\theta$
b. Yawing rate, $q=\dot{\theta}C_\Phi+\dot{\Psi}C_\theta S_\Phi$,
c. Pitching rate, $r=\dot{\Psi}C_\theta C_\Phi-\dot{\theta}S_\Phi$
d. Pitch Angle, $\dot{\theta}=qC_\Phi-rS_\Phi$
e. Roll Angle, $\dot{\Phi}=p+qS_\Phi T_\theta+rC_\Phi T_\theta$
f. Yaw Angle, $\dot{\Psi}=(qS_\Phi+rC_\Phi)\sec\theta$

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.

$u=u_o+\Delta u \quad v=v_o+\Delta v \quad w=w_o+\Delta w$
$p=p_o+\Delta p \quad q=q_o+\Delta q \quad r=r_o+\Delta r$
$X=X_o+\Delta X \quad M=M_o+\Delta M \quad Z=Z_o+\Delta Z$

$$\delta = \delta_o+\Delta\delta \qquad (4)$$

For convenience the reference flight condition is assumed and the propulsive forces are assumed to remain constant. This implies that, $v_o=p_o=q_o=r_o=\Phi_o=\Psi_o=w_o=0$. After linearization the (5), (6) and (7) are obtained.

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

$$-Z\Delta u + \left[(1-Z_w)\frac{d}{dt}-Z_w\right]\Delta w - \left[(u_o+Z_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta = Z_{\delta e}\Delta\delta_e \qquad (6)$$

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

By manipulating the (5), (6), (7) 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 (8)

$$\frac{\Delta q(s)}{\Delta\delta_e(s)} = \frac{-(M_{\delta e}+M_\alpha Z_{\delta e}/u_0)s-(M_\alpha Z_{\delta e}/u_0-M_{\delta e}Z_\alpha/u_0)}{S^2-(M_q+M_{\dot\alpha}+Z_\alpha/u_0)s+(Z_\alpha M_q/u_0-M_\alpha)} \qquad (8)$$

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 change in elevator angle in the following way.

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

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

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}\cdot\frac{\Delta q(s)}{\Delta\theta(s)} \qquad (11)$$

Therefore the transfer function of the pitch control system is obtained in (12) and (13) respectively.

$$\frac{\Delta\theta(s)}{\Delta\delta_e(s)} = \frac{1}{s}\cdot\frac{-(M_{\delta e}+M_{\dot\alpha}Z_{\delta e}/u_0)s-(M_\alpha Z_{\delta e}/u_0-M_{\delta e}Z_\alpha/u_0)}{S^2-(M_q+M_{\dot\alpha}+Z_\alpha/u_0)s+(Z_\alpha M_q/u_0-M_\alpha)} \qquad (12)$$

$$\frac{\Delta\theta(s)}{\Delta\delta(s_e)} = \frac{11.7304s+22.578}{s^2+4.9676s^2+12.941s} \qquad (13)$$

The transfer function can be represented in state-space form and output equation as state by (14) and (15).

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

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

III. METHODOLOGY

In this section four feedback control schemes are proposed and are described in detail which is PID, self-tuning fuzzy PID, QFT Controller and GA based QFT controller for control the pitch angle of an aircraft.

A. PID Controller:

Proportional integral derivative controller (PID) regarded as the standard control structure of the classical control theory. PID is a genetic control loop feedback mechanism widely used in industrial control systems. The performance specification of the system can be improved by adjusting the value of gain K_P, K_i and K_d. The selection of these values will cause for the variation in observed response because each component has its own special purposes. The mathematical description of linear relationship exist between the controller output, u(t) and the error, e(t) is expressed as (16) and (17) where K_P = proportional gain, K_i = integral gain, K_d =derivative gain, T_i=integral time, T_d = derivative time.

$$u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt} \qquad (16)$$

$$u(t)=K_p\left(e(t)+\frac{1}{T_i}\int e(t)dt+T_d\frac{de(t)}{dt}\right) \qquad (17)$$

B. Self-tuning Fuzzy PID:

Many researches put forward new PID control strategies based on some intelligent algorithms especially using fuzzy logic concepts. Self-tuning fuzzy PID controller is a PID controller that employs the Fuzzy Interface System (FIS) to tune the parameters of K_p, K_i and K_d according to error (e) and derivative of error (δ_e).

In self tuning fuzzy PID controller, the rules are designed based on characteristics of aircraft pitch control and properties of the PID controller. The parameters of K_p, K_i and K_d must be calculated by using fuzzy tuner. The fuzzy tuner has two inputs: error (e) and derivative of error (δ_e), and three outputs: K_p, K_i and K_d .

The membership functions of these inputs fuzzy sets are shown in Fig. 3. The fuzzy sets for each input variables consisting of seven linguistic variables:
e = {NB, NM, NS, ZE, PS, PM, PB}
δ_e = { NB, NM, NS, ZE, PS, PM, PB }

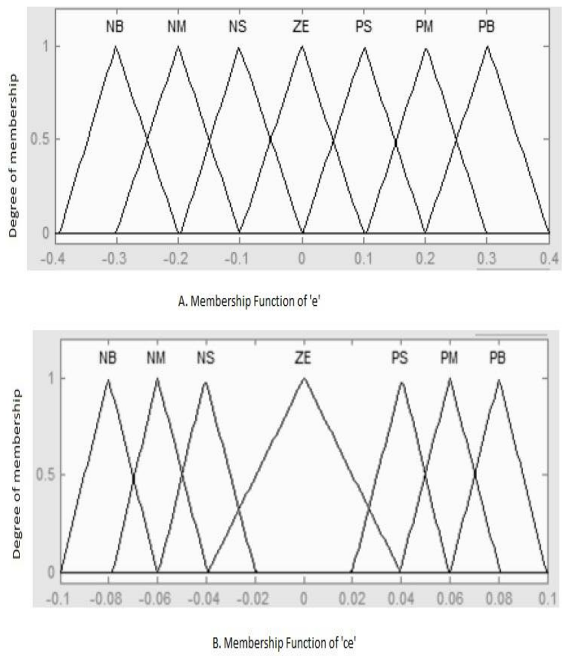

Figure 3. membership function of e(t)and $\Delta e(t)$

The membership functions of outputs K_p, K_i and K_d are shown in Fig. 4. The linguistic variables of these outputs are assigned as:
K_p={N, Z, P}, K_p={ N, Z, P }, K_d={ N, Z, P }

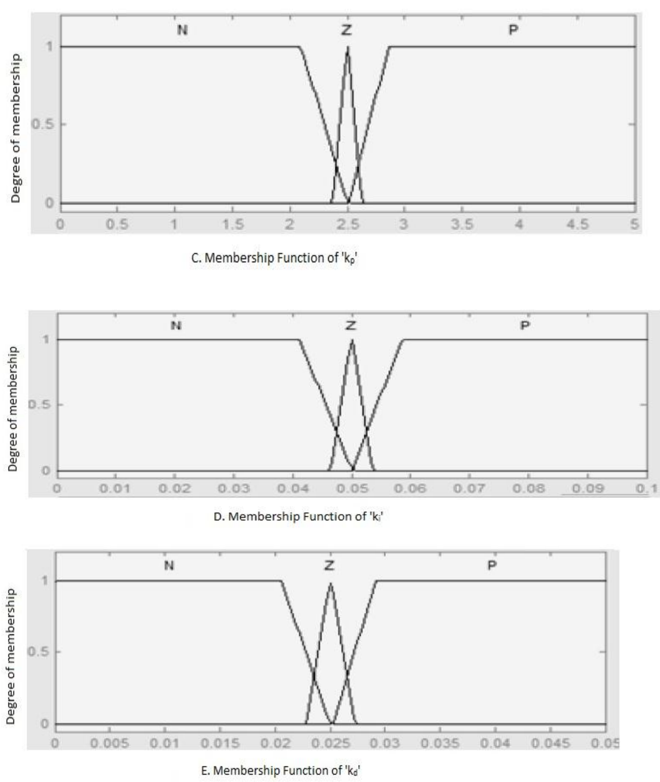

Fig.4. Membership function of K_p, K_i and K_d

Generally, fuzzy rules are dependent on the plant to be controlled and the summary of designer's knowledge and experience. Regarding to the above fuzzy sets of inputs and output variables, the fuzzy control rules of K_p, K_i and K_d are shown in Table II and composed as follows:
Rule i: if $e(i)$ ia A_{zi} then $K_p = B_i$ and $K_d = C_i$ and $K_i = D_i$

Table II. Rules for Self-Tuning Fuzzy PID

δ_e \ e (K_p, K_i, K_d)	NB	NM	NS	ZE	PS	PM	PB
NB	P N P	Z P Z	N P N	N N N	N P N	Z P Z	P N P
NS	P N P	P Z Z	Z P Z	N p N	Z P Z	P Z Z	P N P
NM	P N P	P N P	Z Z Z	N P N	Z Z Z	P N P	P N P
ZE	P N P	P N P	P N P	Z Z Z	P N P	P N P	P N P
PS	P N P	P N P	Z Z Z	N P N	Z Z Z	P N P	P N P
PM	P N P	P Z Z	Z P Z	N P N	Z P Z	P Z Z	P N P
PB	P N P	Z P Z	N P N	N P N	P N P	Z P Z	P N P

The controller transfer function that has been obtained from Self-tuning Fuzzy PID controller is given by

$$Gc(s) = \frac{0.8s^2 + 4.12s + 0.02}{s}$$

C. QFT Controller Design:

The general structure of QFT design is shown in Fig.5.

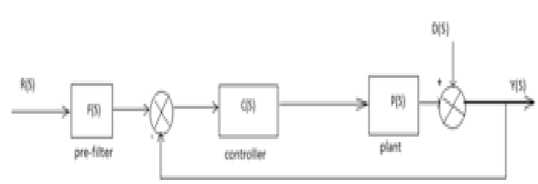

Fig.5. QFT Controller Design

Here, P(s) is the set of transfer functions {p(s)}, which describes the region of plant parameter uncertainty, C(s) is the cascade compensator, and F(s) is an input pre-filter.

The output Y(s) is required to track the command input R(s) and reject the external disturbance D(s). The compensator C(s) is to be designed so that the variation of R(s) to the uncertainty in the plant P is within allowable tolerances, the robustness criterion is ensured and the disturbance rejection is requirement is met. In addition, the pre-filter properties of F(s) must be designed to tailor the responses to meet the tracking specification requirements.

QFT design method is based upon the following steps:

- Specifying the tolerances in frequencies domain(time domain tolerances should be converted into corresponding frequency domain tolerances) by means of set plant transfer functions and closed-loop control ratios;
- Determining the loop transmission functions and pre-filter functions to satisfy the various resulting bounds corresponding to tolerances.

The controller transfer function that has been obtained from QFT controller is: $Gc(s) = \frac{144.607(s+1.1804)(s+3.3658)}{(s+202.044)(s+0.10529)}$

D. GA based QFT Design:

(i) Genetic Algorithm:

The steps involved in creating and implementing a genetic algorithm: Generate an initial, random population of individuals for a fixed size [10].

1. Initialize population
2. Evaluate their fitness.
3. Select the fittest members of the population.
4. Reproduce using a probabilistic method (e.g., roulette wheel).
5. Implement crossover operation on the reproduced chromosomes (Choosing probabilistically both the crossover site and the mates).
6. Execute mutation operation with low probability.
7. Repeat step 2 until a predefined convergence criterion is met.

(ii) Definition of objective function for automated loop shaping in QFT:

In the proposed approach, the controller structure is predetermined and given by (Chen et al.,1999).

$$C(s) = \frac{b_r s^r + \cdots b_1 s + b_0}{a_m s^m + \cdots + a_1 s + a_0} \quad (19)$$

The coefficients $b_r \ldots. b_1, b_0$ and $a_m \ldots. a_1, a_0$ are searched by the GA algorithm.

The objective function is given by Equation (20).

$$J = \beta_1 J_{hfg} + \sum_{i=1}^{N} (\beta_{2i} J_{sta} + \beta_{3i} J_{bi}) + \beta_4 J_{gef}, \quad (20).$$

Where J_{bi} are the robust stability indices, J_{sta} is the stability index, J_{hfg} is the high-frequency gain, and J_{gef} is the index for upper limit in gain crossover frequency for compensated loop transmission, β_1, β_{2i}, β_{3i}, and β_4 are weighting factors.

Tracking specifications:

Overshoot < 2%

Rise time 1s < t_r < 3s

Steady state error Nil

Stability specifications:

Gain margin >5.25 dB

Phase margin > 49.25deg

The robust stability specifications are determined as

$$\left| \frac{P(s)G(s)H(s)}{1 + P(s)G(s)H(s)} \right| \le \mu = 1.2$$

For GA-enabled automatic loop shaping, a PID controller is chosen as:

$$G_C(s) = \frac{a_2 s^2 + a_1 s + a_0}{s}$$

The controller transfer function that has been obtained from the GA based QFT controller is given by

$$Gc(s) = \frac{0.4875s^2 + 2.5183s + 1.0338}{s}$$

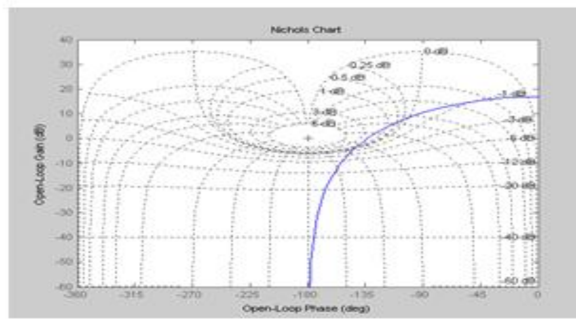

Fig. 6. Nichols Plot for plant P(s)

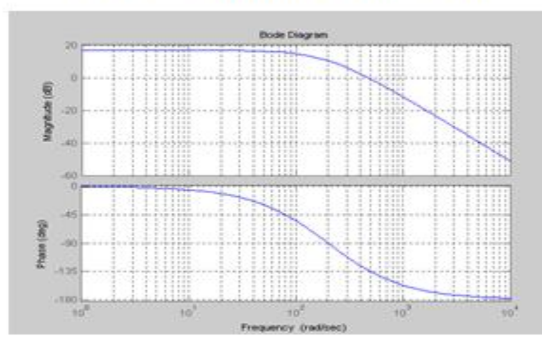

Fig.7. Bode plot representation of P(s)

Fig.8. Plant template generation

Nichols plot representation of the given system is shown in Fig.6 and corresponding Bode plot representation, template generation are shown in Fig.7 and 8.

IV. IMPLEMENTATION AND RESULTS

A unit step command is required in order for pitch angle to follow the reference value. The parameters value of K_p, K_i and K_d are turned by using signals from fuzzy logic block based on the change of error between reference signals and output signals.

System response namely pitch angle are observed in this work. The performances of different controller schemes are assessed in term of time response specification. The output of simulation for the closed loop system response under Self-tuning fuzzy PID controller , QFT controller and GA based QFT controller are shown in Fig.9 ,Fig.10 and Fig.11.

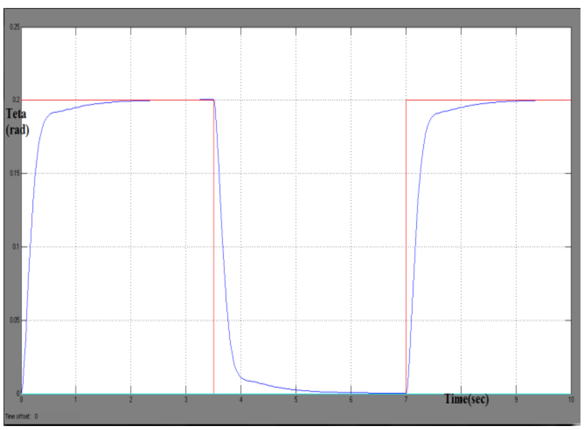

Fig.9. Pitch angle response with Self-tuning Fuzzy PID controller

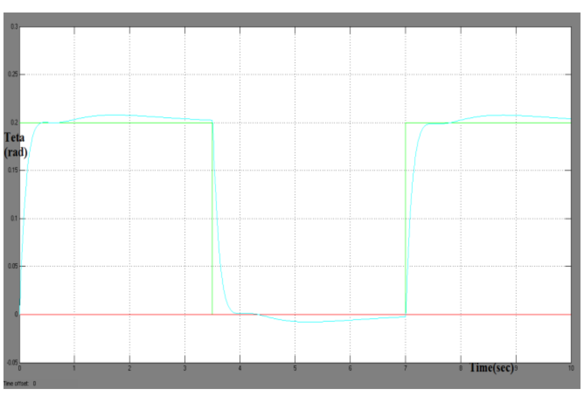

Fig.10. Pitch angle response with QFT controller

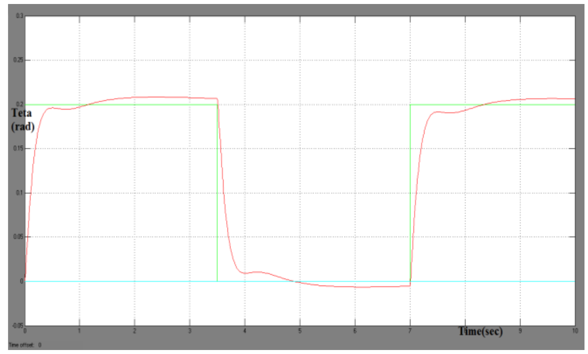

Fig.11. Pitch angle response with GA based QFT controller

In Fig.10, two inputs have been applied to self-tuning fuzzy PID 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, δ_e which generated by the derivation of the error. As depicted from Fig.10, it can be observed that the pitch angle follows the reference value respectively. The self-tuning fuzzy PID controller is able to give a good response without producing any overshoot. The response is comparatively faster compared to PID controller with delay time , T_d about 0.1699 s, settling time, T_s about 0.3819 s and rise time, T_r about 2,39 s. The results also demonstrated, self-tuning fuzzy PID controller can eliminate the effect of disturbances in the system up to 0.004%.

TABLE III. Summary of Performance Characteristics of Pitch angle

Type of controller	Pitch angle (radian) response				
	Delay time(sec)	Rise time (sec)	Settling time (sec)	(%Mp)	(e_{ss})
Self-tuning fuzzy PID Controller	**0.1699**	**0.239**	**0.3819**	**0**	**0.004**
GA based QFT controller	**0.1243**	**0.224**	**0.354**	**0**	**0.002**
QFT Controller	**0.0783**	**0.204**	**0.319**	**0**	**0.0015**

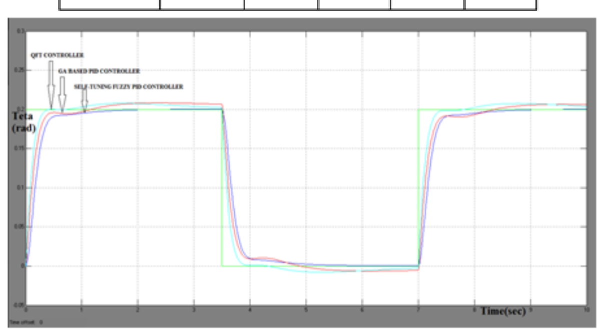

Figure 12. Performance comparison of all controllers

V. CONCLUSION

Modeling is done on an aircraft pitch control and self-tuning PID is proposed successfully. The proposed control schemes have been implemented within simulation environment in Matlab and Simulink. Performance of the control schemes have been evaluated in term of time domain specification. The results obtained, demonstrate that the effect of disturbances in the system can successfully be handled by QFT controller and GA based QFT controller. Based on the results, the system responses indicate the performance of pitch control system using QFT controller has been improved compared to self-tuning fuzzy PID controller. For further research, effort can be extended and devoted through adding another element that makes up the control system, following by adopting the control scheme in practical application.

REFERENCES

[1]. Nurbaiti Wahid , Nurhaffizah Hassan, "Self-tuning fuzzy PID controller Design for Aircraft pitch control", International Conference on Intelligent systems Modelling and Simulation,2012.
[2]. R.C. Nelson, "Flight Stability and Automatic Control", McGraw Hill, 2nd edition.
[3]. J.K. Shiau and D.M. Ma, "An Autopilot Design for the Longitudinal Dynamics of a Low Speed Experimental UAV using Two Time Scale Cascade Decomposition", Transaction of the Canadian Society for Mechanical Engineering, Vol 33, No 3, 2009.
[4]. Chen, F.C. and Khalil, H.K., "Two-Time-Scale Longitudinal Control of Airplanes Using Singular Perturbation'', AIAA, Journal of Guidance, Navigation, and Control, Vol. 13, 1990, No. 6, pp. 952- 960.
[5]. Ekprasit Promtun, Sridhar Seshagiri, "Sliding Mode Control of Pitch Rate of an F-16 Aircraft", International Journal on Applied Science, Engineering and Technology, Vol 5, 2009, No 5.
[6]. M. Myint, H.K. Oo, Z.M. Naing and Y.M Myint, "PID Controller for Stability of Piper Cherokee's Pitch Displacement using MATLAB", International Conference on Sustainable Development: Issues and prospects for the GMS, China, 2008.
[7]. C. C. Lee, "Fuzzy Logic in Control System: Fuzzy Logic Controller I", System, Man and Cybernatics, IEEE Transaction, Vol. 20, 1990, pp. 404-418.
[8]. M. Kuzelkaya, I. Eksin and E. Yesil, "Self-tuning of PID-type Fuzzy Logic Controller Coefficient via Relative Rate Observer", Engineering Applications of Artificial Intelligence, vol 16, 2003, pp. 227-236.
[9]. C. Jianwen, H. Zhanjun, S. Jingcun, P. Changjian, "Simulation of Fuzzy Self-tuning PID Control Based on Simulink", Applied Mechanics and Materials, Vols. 52-54, 2011, pp. 1644-1649.
[10]. The Math Works Inc., Genetic Algorithms and Direct Search TOOLBOX, CD-ROM Manual, 2004.
[11]. Horowitz, I.M, Synthesis of Feedback Systems, Academic Press, New York, 1963.
[12]. C. H. Houpis, S. J. Rasmussen, and M. Garcia- Sanz, Quantitative Feedback Theory, Fundamentals and Applications, 2nd Ed. New York: Taylor & Francis, 2006.