

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/312323342>

Modeling and Simulation of Longitudinal Autopilot for General Aviation Aircraft

Conference Paper · May 2016

DOI: 10.1109/ICIEV.2016.7760051

CITATIONS

12

READS

5,263

4 authors, including:



Md Ashiqur Rahman Laskar

Arizona State University

35 PUBLICATIONS 516 CITATIONS

[SEE PROFILE](#)



Md Tanjemul Islam

Jahangirnagar University

4 PUBLICATIONS 14 CITATIONS

[SEE PROFILE](#)



Md. Shah Alam

University of Toledo

7 PUBLICATIONS 136 CITATIONS

[SEE PROFILE](#)

MODELING AND SIMULATION OF LONGITUDINAL AUTOPILOT FOR GENERAL AVIATION AIRCRAFT

Md. Tanjemul Islam¹, Md. Shah Alam², Md. Ashiqur Rahman Laskar³, Atul Garg⁴

¹⁻⁴Department of Aeronautical Engineering

Military Institute of Science and Technology (MIST), Dhaka, Bangladesh

Email: tanjemul11@gmail.com, shahmistae04@gmail.com, ashiq22050@gmail.com, atulgarg@gmail.com

Abstract- From the dawn of advanced aerospace technology, the aspect of stability and automated control is an important field of research interest providing ease of handling and friendly assistance for piloting. Considering this challenging aspect, development of automated control system is chosen for this research. The aim of this paper is to design a longitudinal autopilot for a general aviation aircraft and to analyze the performance of the developed model both for normal condition and atmospheric disturbance. To improve the overall performance, stability of the system and to overcome the atmospheric disturbance a compensator along with a PID controller has been designed. Simulation results of MATLAB Simulink have been also analyzed.

Keywords- Elevator, Pitch controller, Autopilot, General aviation aircraft, MATLAB

I. INTRODUCTION

An autopilot is designed depending on the control surfaces of the aircraft. They are broadly classified as longitudinal autopilot and lateral autopilot. Pitch angle and altitude of the aircraft is controlled by longitudinal autopilot. On the other hand, roll and yaw movements are controlled through lateral autopilot. In case of lateral-directional mode, more than one control surface contributes to perform the action. But in case of longitudinal modes pitch angle and altitude depend only on the contribution of elevator. For these reasons lateral autopilot is much more complicated than the longitudinal autopilot. That's why model of a longitudinal autopilot has been chosen in this paper which will control the aircraft at normal condition and also in atmospheric disturbance by controlling pitch angle and altitude at the same time. General aviation covers a large range of activities, both commercial and non-commercial, including flying clubs, flight training, agricultural aviation, light aircraft manufacturing and maintenance [1]. Considering these factors, decision has been made to

model a longitudinal autopilot for general aviation aircraft. Autopilot is now the object of great interest in the field of research because of its newly increasing applications in aircrafts, missiles, space crafts, ships, UAVs and others. Previously various researches have been carried out on autopilot and the performances of autopilot. One of the research on missile autopilot describes about the design of longitudinal autopilot using back stepping approach. Two autopilot topologies are proposed in this approach one is angle of attack (AOA) autopilot and another one is acceleration autopilot. The nonlinear missile longitudinal dynamics is dealt with firstly to meet the strict feedback loop [2]. Another research has been done on the three loop autopilot design and simulation. In order to realize missile real-time change flight trajectory, a three loop autopilot has been set up. After the analysis of performance, the results show that autopilot gains played a good job in the flight trajectory, autopilot satisfied the flight index [3]. One research shows linear active disturbance rejection control approach for near space vehicle autopilot because the conventional PID controller parameters are difficult to be decided on the dynamics of the near space vehicle within a large flight envelope. The approach is employed to a hypersonic near space vehicle autopilot. The numeral simulations show that the proposed approach has a good performance on frequency domain and time domain. The angle of attack command is tracked very well, and the controller parameters are easy to be determined [4]. One of research has been done on design and simulation of longitudinal autopilot modes for a conventional aircraft. There are different modes of automatic longitudinal flight controls. Among those pitch attitude holds, altitude hold and vertical speed hold mode autopilots are implemented in which controller is designed for each of these modes. By the use of this controller, the system performance is improved [5].

From the above studies it can easily be understood that autopilot is such a system which is very important to control air vehicles automatically and to reduce the work load of human being. Considering these importance, an attempt has been made in this paper to model such an autopilot which can control the pitch angle and altitude of a general aviation aircraft. The designed autopilot of this paper is also able to compensate the sudden disturbance errors. Performances are analyzed for type 0 system in this paper. If the aircraft displaced from its straight and level flight condition by the strike of sudden gust, then how the performance of the aircraft will change to keep the aircraft in its equilibrium is also analyzed here. Various simulations have been done using MATLAB Simulink. The results for the pitch angle response of the aircraft are analyzed and the performance is measured in terms of rise time (Tr), settling time (Ts), percentage overshoot (%OS), steady state error (e_{ss}) for pitch angle response of the aircraft.

II. AIRCRAFT DYNAMICS

The xz-plane has been considered as a plane of symmetry. The performance of the aircraft can adequately be described by assuming the aircraft to a point mass concentrated at the aircraft's center of gravity (cg). Then assuming that the origin of axis system is the center of gravity of the aircraft and perturbations from equilibrium are small. Also assuming that the earth and atmosphere are fixed in the inertial space and mass (m) is constant ($dm/dt = 0$). The aircraft has been considered as a rigid body. Considering these, the longitudinal equations of motion can be written as following-

$$\left(\frac{mV_T}{S_q}\dot{u} - C_{xu}u\right) + \left(-\frac{c}{2V_T}C_{x\dot{\alpha}}\dot{\alpha} - C_{x\alpha}\alpha\right) + \left(-\frac{c}{2V_T}C_{xq}\dot{\theta} - C_w(\cos \theta)\theta\right) = C_{Fxa} \quad (1)$$

$$-(C_{zu}u) + \left(\frac{mV_T}{S_q} - \frac{c}{2V_T}C_{z\dot{\alpha}}\right)\dot{\alpha} - C_{z\alpha}\alpha + \left(-\frac{mV_T}{S_q} - \frac{c}{2V_T}C_{zq}\right)\dot{\theta} - C_w(\sin \theta)\theta = C_{Fza} \quad (2)$$

$$(C_{mu}u) + \left(\frac{c}{2V_T}C_{m\dot{\alpha}}\dot{\alpha} - C_{m\alpha}\alpha\right) + \left(\frac{I_y}{S_q c}\ddot{\theta} - \frac{c}{2V_T}C_{mq}\dot{\theta}\right) = C_{ma} \quad (3)$$

Where \dot{u} represents the forward velocity, $\dot{\alpha}$ represents the angle of attack and $\dot{\theta}$ represents the pitch angle. m, c, q, S and V_T represents mass, mean aerodynamic chord, dynamic pressure, span area and total forward velocity in the longitudinal direction. C_{xu} , $C_{x\dot{\alpha}}$, $C_{x\alpha}$, C_{xq} , C_w , C_{zu} , $C_{z\dot{\alpha}}$, $C_{z\alpha}$, C_{zq} , C_{mu} , $C_{m\dot{\alpha}}$, $C_{m\alpha}$ and C_{mq} are the stability derivatives [6]. To obtain the transient solution, consider the external inputs $C_{Fxa} = C_{Fza} = C_{ma} = 0$. Now, applying the Laplace transform to equation 1-3 with initial condition zero yields-

$$\left(\frac{mV_T}{S_q}s - C_{xu}\right)u + \left(-\frac{c}{2V_T}C_{x\dot{\alpha}}s - C_{x\alpha}\right)\alpha + \left(-\frac{c}{2V_T}C_{xq}s - C_w(\cos \theta)\right)\theta = 0 \quad (4)$$

$$-(C_{zu}u) + \left[\left(\frac{mV_T}{S_q} - \frac{c}{2V_T}C_{z\dot{\alpha}}\right)s - C_{z\alpha}\right]\alpha + \left[\left(-\frac{mV_T}{S_q} - \frac{c}{2V_T}C_{zq}\right)s - C_w(\sin \theta)\right]\theta = 0 \quad (5)$$

$$-(C_{mu}u) + \left(\frac{c}{2V_T}C_{m\dot{\alpha}} - C_{m\alpha}\right)\alpha + \left(\frac{I_y}{S_q c}s^2 - \frac{c}{2V_T}C_{mq}s\right)\theta = 0 \quad (6)$$

A quadratic equation is obtained after solving equation 4, 5 and 6. The solution of this quadratic equation gives two quadratic factors, one is short period mode and another one is phugoid mode. The frequency of the oscillation for the phugoid is much lower than that observed for the short period mode. If the short period mode is unstable, it will generally be impossible for the pilot to safely control the aircraft for any period of time. The period is so short that the speed does not have time to change, so the oscillation is essentially an angle-of-attack variation. Since this mode is usually highly damped and disturbance will be considered in this research, its frequency and damping are very important in the assessment of aircraft handling. Moreover, the short period frequency is strongly related to the airplane's static margin. In the simple case of straight line motion, the frequency is proportional to the square root of $C_{m\alpha} / C_L$. Therefore, only short period mode is considered here. Now substituting $u = 0$ in the longitudinal equation of motion since the short period oscillation occurs at almost constant forward speed. The equation along X axis does not contribute to the short period oscillation. With these assumptions and neglecting $C_{z\alpha}$, the equations become :

$$\left(\frac{mV_T}{S_q}s - C_{z\alpha}\right)\alpha + \left[\left(-\frac{mV_T}{S_q} - \frac{c}{2V_T}C_{zq}\right)s - C_w(\sin \theta)\right]\theta = C_{z\partial e}\partial e \quad (7)$$

$$\left(\frac{c}{2V_T}C_{m\dot{\alpha}}s - C_{m\alpha}\right)\alpha + \left(\frac{I_y}{S_q c}s^2 - \frac{c}{2V_T}C_{mq}\right)\theta = C_{m\partial e}\partial e \quad (8)$$

Where ∂e is the deflection of elevator and $C_{z\partial e} = (c/l_e)C_{m\partial e}$. From the geometrical figures of the aircraft the value of c/l_e can be found [7].

TABLE I. VALUES OF THE COEFFICIENTS [7]

V_T	C_{mq}	$C_{m\delta e}$	$C_{z\alpha}$	s	I_y	m
176	-9.96	-.923	-4.49	184	3000	85.403
C	$C_{z\delta e}$	q	$C_{m\dot{\alpha}}$	C_{zq}	$C_{m\dot{\alpha}}$	$C_{w\sin\theta}$
5.7	-.189	36.82	-4.36	0	-.673	0

After substituting the values from the table, equations 7 and 8 become:

$$(2.2189 \rho + 4.49)\alpha - (2.2189 \rho)\theta = -0.1887 \delta_e \quad (9)$$

$$(-0.0706 \rho + 0.673)\alpha + (0.07769 \rho^2 + 0.1613 \rho)\theta = -0.923 \delta_e \quad (10)$$

Now, solving equation 9 and 10 the desired transfer function is obtained as following:

$$\frac{\theta(s)}{\delta_e} = -\frac{11.8(s + 1.97)}{(s^2 + 5s + 12.96)} \quad (11)$$

III. MODELING PITCH DISPLACEMENT AUTOPILOT

Compensator Design:

Compensators are not only used to improve the transient response of a system but they are also used independently to improve the steady-state error characteristics. To design the compensator, automated tuning method is used using MATLAB SISO Tool. The SISO Design Tool simplifies the task of designing and tuning compensators. There are five automated tuning methods in the SISO Design Tool to help designing an initial stabilizing compensator for a SISO loop on-the-fly or refine existing compensator design so that it satisfies a certain user-defined design specification. The obtained compensator's transfer function is,

$$C = \frac{49.394 * ((1 + 0.08s) * (1 + 0.39s + 0.28s^2))}{s * (1 + 0.51s) * (1 + 0.035s)} \quad (12)$$

PID Controller Design:

Controller is the element in the system which regulates, directs or commands the entire plant according to the error signal generated. The main task of a controller is to monitor the dynamic system behavior and direct the system to the required operating condition. The PID Tuner automatically computes a linear model of the plant in the Simulink model. It considers the plant to be the combination of all blocks

between the PID controller output and input. Thus, the plant includes all blocks in the control loop, other than the controller itself. By just clicking "Tune" the system automatically brings the PID Tuner tool. The resulting PID controller can be shown as:

$$PID = \frac{1.191e04s^2 + 3.251e05s + 2.218e06}{s^2 + 1.669e04s} \quad (13)$$

Simulink Modeling:

The reference pitch angle set for the autopilot is always compared with the actual pitch angle at that moment. Thus error signal is produced which is fed to the controller and a calculated correction is given by the elevator servo. Thus desired pitch angle is maintained. For modeling the "Pitch displacement autopilot" MATLAB Simulink has been used. The model of the Pitch displacement autopilot has been developed as following-

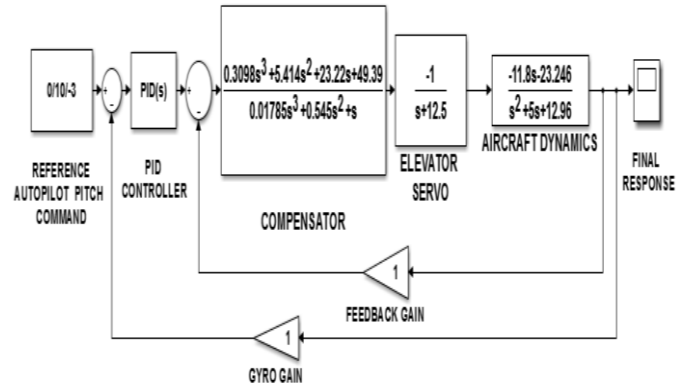


Figure 1. Pitch displacement autopilot.

Adding any kind of external gust or disturbance it can be further modified as,

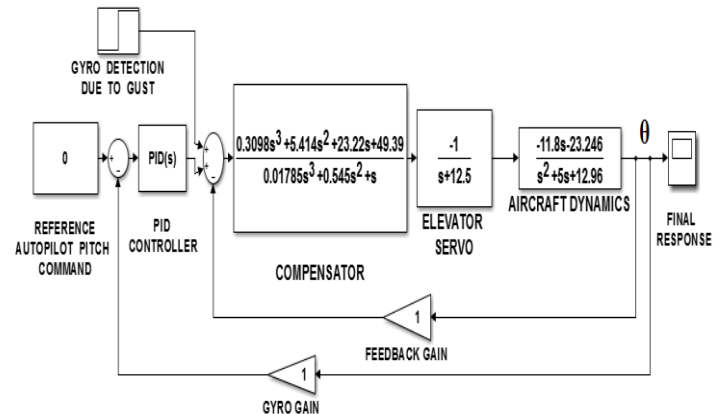


Figure 2. Pitch displacement autopilot with disturbance.

In this final Simulink model of pitch displacement or longitudinal autopilot, reference is a constant block where autopilot command will be put. Inner closed loop has simply a unity feedback gain. The change in pitch attitude due to atmospheric disturbance like gust is sensed by a gyroscope and the gyroscopic detected signal is fed at the input of inner loop. The Inner loop provides the support to reduce errors at a minimum that occur in control surface actuator or aircraft dynamics since those are not ideal. Outer closed loop gives the final correction to maintain aircraft pitch attitude (angle) according to the autopilot command. To see the final response of the whole system a scope block has been added at the end of the model.

IV. SIMULATION RESULT ANALYSIS

Simulation is the imitation of the operation of a real-world process or system over time [8]. In this study, all the simulations are done for 10 sec.

Response in different pitch angle command conditions without disturbance:

At the early portion of this result analysis, considering that a general aviation aircraft is flying where there is no disturbance like gust. Now, three types of command condition have been considered for pitch control autopilot. Autopilot pitch command (Reference) as 0 degree for level flight, +10 degree for pitch up condition, -3 degree for pitch down condition. The response of the designed model for each condition is simulated and output theta, θ (Pitch angle) is taken from the scope block which are shown below respectively. Simulating the model shown in fig-1, following three figures are obtained.

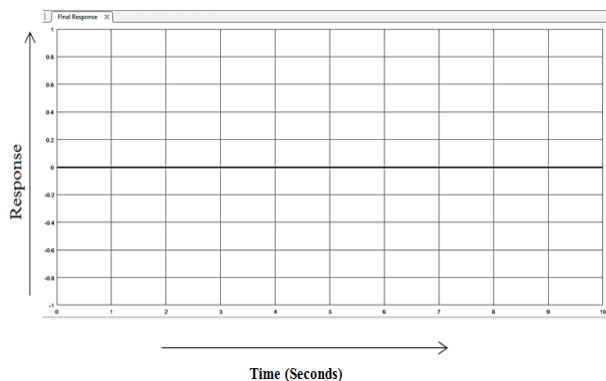


Figure 3. Response for level flight (0 deg.) command condition without disturbance.

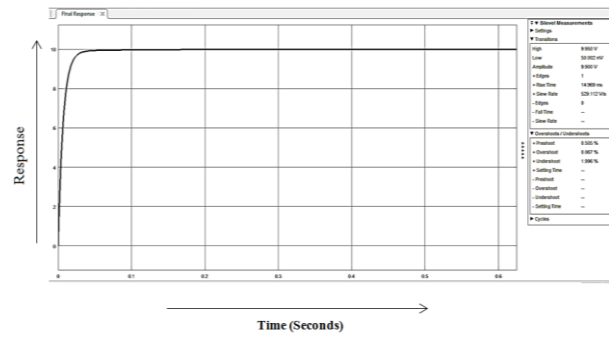


Figure 4. Response for Pitch up (+10 deg.) command condition without disturbance.

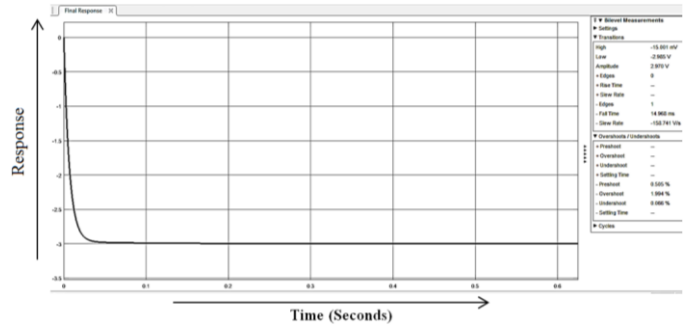


Figure 5. Response for Pitch down (-3 deg.) command condition without disturbance.

From the above figures, it is observed that rise time is 14.969 ms and percentage of overshoot is 0.069% for pitch up condition. For pitch down condition rise time (Fall time) is 14.968 ms and percentage of overshoot is 1.994 %. So, designed model is more reliable in pitch up condition than pitch down condition. Also, level flight response is steady and perfect.

Response in different pitch angle command conditions with standard disturbance:

In this part comparison has been made between conventional model and designed model by considering the responses at different pitch angle command conditions. Here disturbance is fed at the input of the inner loop. Unit step is used as standard input which is acting as the gyroscope detection of aircraft pitch angle change due to gusts or disturbances. Simulating the models shown in fig. 1 & fig. 2, following six figures are obtained.

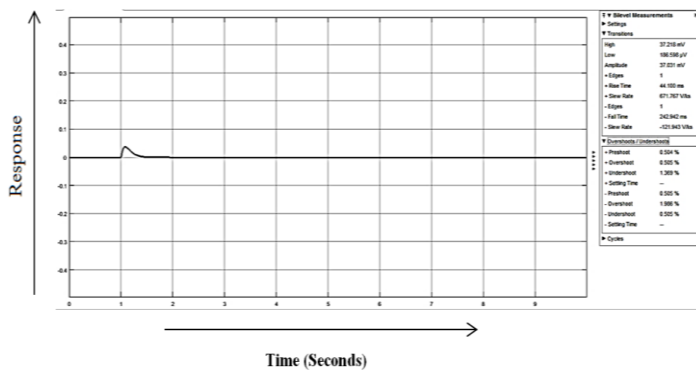


Figure 6. Response of the designed model at level flight command condition (Pitch angle=0 deg.).

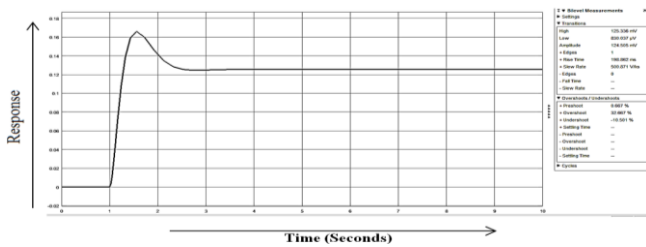


Figure 7. Response of the conventional model at level flight command condition (Pitch angle=0 deg.).

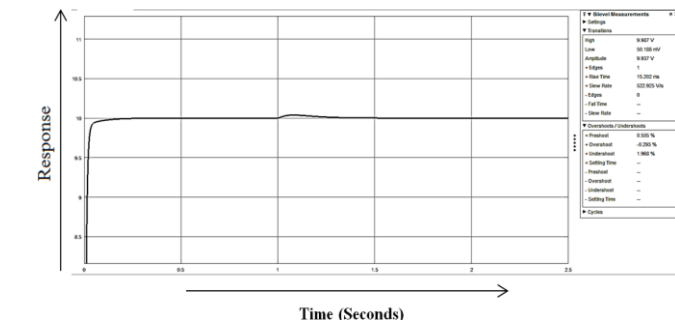


Figure 8. Response of the designed model at pitch up command condition (Pitch angle= +10 deg.).

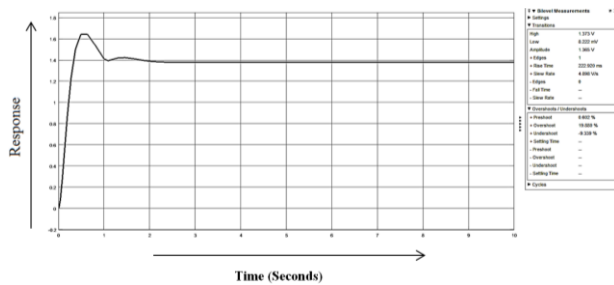


Figure 9. Response of the conventional model at pitch up command condition (Pitch angle= +10 deg.).

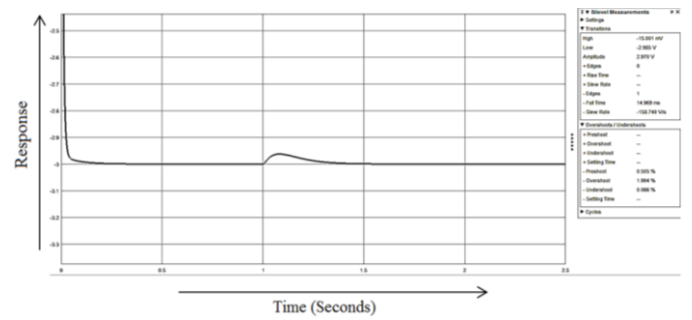


Figure 10. Response of the designed model at pitch down command condition (Pitch angle= -3 deg.).

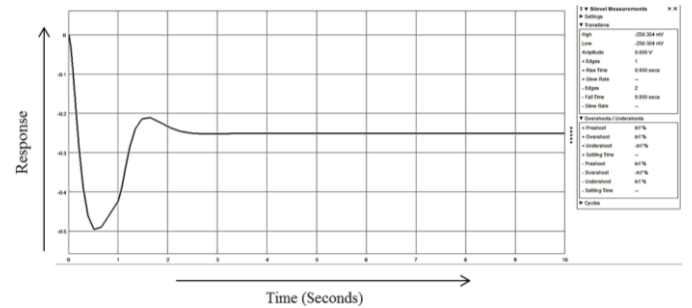


Figure 11. Response of the conventional model at pitch down command condition (pitch angle=-3 deg.).

The above Simulation graphs clearly represent that newly designed automatic pitch control model has advantages over previous one with highly reduced percentage of overshoot and rise time. For example, at +10 degree pitch up condition some parameters are listed below:

TABLE II. PARAMETERS OF PERFORMANCE CHARACTERISTICS

Parameter	Designed model	Conventional model
Rise Time	15.120 ms	198.862 ms
% Overshoot	0.312 %	32.667%
% Preshoot	0.505%	0.667%
% Undershoot	1.553%	10.501%

Response in different pitch angle command conditions with rectangular pulsed disturbance:

Now rectangular shaped pulse is introduced instead of standard input as disturbance. Pulse width of it is 3 sec and amplitude is 1. Pulse width indicates the duration of faced disturbance.

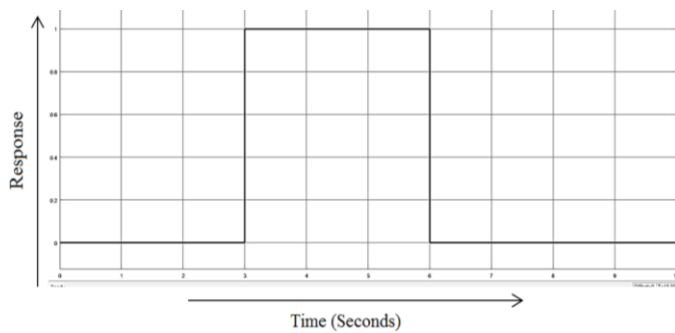


Figure 12. Rectangular shaped pulse as disturbance.

Simulation is repeated and response is observed. This time only level flight that means 0 degree pitch angle command condition is considered. Designed model shows more stable response than conventional model. Amplitude of response of designed model is 0.04 while 0.17 for other. From the following figures, it can be seen that designed model takes total 1 sec to compensate a disturbance (Gust) of 3 sec duration where 0.5 sec at the beginning(3-3.5 sec) of gust and rest 0.5 sec at the ending(6-6.5 sec) of gust.

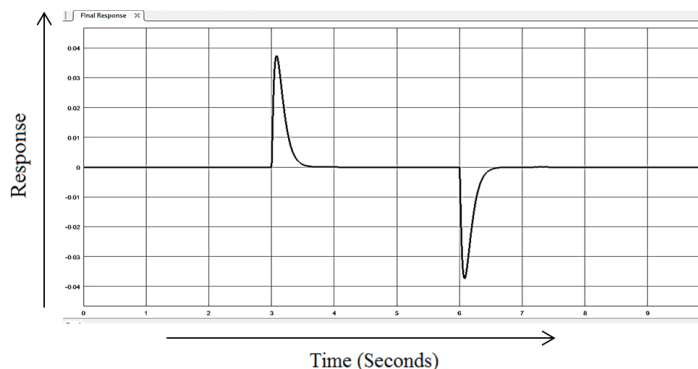


Figure 13. Response of the designed model at level flight command condition (Pitch angle=0 deg.).

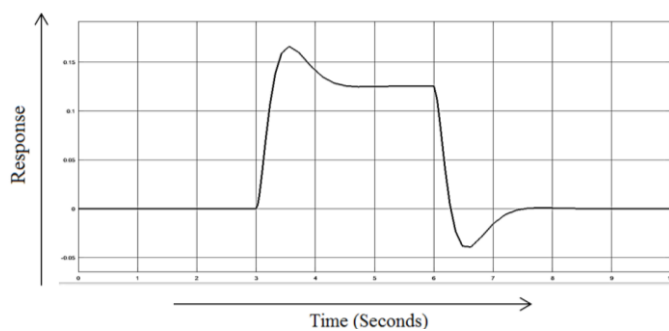


Figure 14. Response of the conventional model at level flight command condition (Pitch angle=0 deg.).

On the contrary, conventional model requires 4.4 sec (3-7.4 sec) to compensate with 3 sec duration disturbance or gust. As a result, designed pitch control or longitudinal autopilot can provide piloting the general aviation aircraft more effectively.

V. CONCLUSION

PID controller Tuning method is utilized to design the PID controller where maximum faster time response and robust transient behavior are emphasized. This designed PID controller has dynamic response compared to other normal controllers. Due to the limitations of the open loop system, a closed loop (Outer loop) system is introduced with efficient characteristics using PID controller. Pitch angle position feedback is used in the outer loop of pitch control to reduce the effect of atmospheric disturbances like gusts. The stability of the whole systems is checked and found as stable. Then Simulink model is generated and simulated for three different autopilot command conditions. The longitudinal autopilot is also tested in the presence of atmospheric disturbances. Comparison between conventional and designed model represents that designed model requires only 1 second for compensating a 3 seconds duration gust where conventional model takes 4.4 seconds. The designed longitudinal autopilot possesses both rise time and settling time in milliseconds with less than 0.5% overshoot. Finally, it can be concluded that a tremendous improvement in overall performance and robustness have been achieved to withstand the desired conditions.

REFERENCES

- [1] Crane, Dale (1997). Dictionary of Aeronautical Terms, third edition, page 238-239. Aviation Supplies & Academics,. ISBN 1- 56027-287-2.
- [2] Fan Jun-fang, Su Zhong, "Missile longitudinal autopilot design using backstepping approach", Aerospace Conference, Big Sky, MT , 6-13 March 2010.
- [3] Chu Hai-rong, Zhang Yue, "Three-loop autopilot design and simulation", International Conference on Mechatronics and Automation (ICMA), Chengdu, 5-8 Aug. 2012.
- [4] Hui Li, Zhide Yin, Yu Fan, Fengyi Li, Chuang Song, "A linear active disturbance rejection control approach for near spacevehicle autopilot", International Conference on Control, Automation and Information Sciences (ICCAIS), Changshu, 29-31 Oct. 2015.
- [5] Solomon Raj, K.D.; Kumar, P.R., "2nd International Conference on Electronics and Communication Systems (ICECS) ", Coimbatore, 26-27 Feb. 2015.
- [6] S.Goyal, "Study of a Longitudinal Autopilot For Different Aircrafts", B.E project report, Punjab Engineering College (DU) Chandigarh, INDIA, 2006.
- [7] R.C. Nelson, Flight Stability and Automatic Control, McGraw-Hill, 1997.
- [8] J. Banks, J. Carson, B. Nelson, D. Nicol (2001). Discrete-Event System Simulation. Prentice Hall. p.3.ISBN 0-13-088702-1.