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Modeling of an Adaptive Controller for an Aircraft Roll Control System using PID, Fuzzy-PID and Genetic Algorithm

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Abstract : *In this paper, an aircraft roll control system for an autopilot that controls the roll angle motion of an aircraft is modeled and simulated using MATLAB/ Simulink. As the roll angle motion is a lateral directional motion, the mathematical model is derived [1]. The control system considered for this roll angle control is PID controller. In this work the PID controller for the roll transfer function of an aircraft is mathematically modeled and simulated for different possible combinations of P, I, D parameters. The simulation octave/results depicts that PID controller needs further tuning to optimize the performance parameters like rise time, settling time and overshoot. Hence the modeled PID controller is tuned using four different tuning methods to get the near to real values of the roll angle system. In spite of tuning for real values of roll angle the PID controller does not satisfy the required criteria. Hence, a proposal of fuzzy controller and fuzzy integrated PID are proposed in order to achieve required performance parameters. From the simulation results, it is observed that PID-GA (Proportional Integral Derivative-Genetic Algorithm) controller delivers the best performance.*

Keywords: *aircraft roll control, fuzzy, fuzzy-PID, lateral directional motion, PID, PID-GA*

I. Introduction

With the successful development of the civilian aircraft, the development of auto-pilots emerged as a future requirement. The auto-pilot (or) auto-flight system is basically made up of sub-systems like Flight Management and Guidance System (FMGS) Flight Augmentation (FAC). All the signals (or) data sensed by different sensors on the flight will be passed through these hardware units for processing. Any hardware failure destroys the properties of the aircraft and the consequences may lead to the loss of an aircraft. Therefore, control failures constitute an important issue to be considered during the design process of a Flight Control System (FCS) [2].

However, in the event of a control failure, the data i.e., corrupted, makes the control operation faulty and the result of action is wrong, which is not desirable. One of the popular techniques to handle hardware failures is hardware redundancy, which increases the cost and maintainability requirements of the system. As an alternative to this redundancy technique, data regeneration by minimizing the error using adaptive controllers may be proposed. The corrected information/data is passed through feedback control system to finally generate error free/fault free data for the control operation. For obtaining the correct data it is proposed to use adaptive controller called Proportional Integral Derivative (PID) controller. The tuning process of PID controller, whereby the optimum values for the controller parameters to be obtained, is a main challenge. Many studies were conducted to find the best way to tune PID parameters in order to get adequate performances such as fast response, zero steady state error, and minimum overshoot/undershoot[3][4]. Different classical tuning methods like automatic, robust, Z-N, IMC tuning methods are implemented. It is observed that the response time and the other performance parameters obtained are not satisfactory.

From the analysis of simulation results of PID controller, it is clear that there is a need for a non-linear controller that can meet the design requirements as highlighted. With the literature survey on different non-linear controllers, an intelligent fuzzy controller has been proposed. With the integration of fuzzy logic and PID controller this proposed intelligent fuzzy-PID controller has the advantages of both the techniques resulting in lesser overshoot, short settling time, zero steady- state error etc., Apart from these parameters improvement, the robustness of the system allows the changes in system parameters and the ability to work with both linear and non-linear systems.

With educational and research purposes in auto-pilot control systems, a test platform that employs MATLAB/ Simulink to run the auto-pilot controller under test is here in proposed in this paper.

II. Motivation

In many applications, the total operation of the plant is mainly dependent upon the controller present in the loop. The input signals are given to the controller along with the reference and the feedback signals. But most of the controllers in many safety critical applications are digital controllers with digital input signals and the digital output as well. In real time the signals obtained are analog signals and these are converted to digital signals for the operation. Before the analog signals are being converted to digital, the analog signals are prone to noise and as the noise mixed analog signals are converted to digital which results in faulty data. Hence, there is a requirement for modeling a controller with analog signals as input and output. Along with the controlling, if any error is forecasted, the error should be minimized or corrected for the proper operation of the plant. For such an operation an adaptive PID Controller is needed and the same is modeled. As a case study, the modeled PID controller is validated for a safety critical application like aircraft Control System for controlling of a primary control action, roll.

The Flight Control System [FCS] is one of the safety critical and most sophisticated Control System. The total operation of FCS depends on the signal data (or) signals that are being sensed by different sensors present on the aircraft. Generally, the sensed signals along with the noise are given to a unit called Air Data Module [ADM] and to Analog to Digital Converter unit for the conversion of sensed analog signals to digital signals. Processing is done in the fourth coming units. Hence, the modeled controllers like PID, fuzzy, fuzzy-PID, PID-GA are incorporated after ADM and the requirement of ADC is minimized. The total operation of FCS is simulated using MATLAB/Simulink as explained in the next headings. The efficient controlling of PID depends on the proper selection of the P, I, D coefficients. For the optimized P, I, D coefficients different tuning methods have been implemented and comparison of different controllers and its parameters are made in this paper.

III. Mathematical model

The equations governing the motion of an aircraft are very complicated set of six nonlinear coupled differential equations. However, under certain assumptions, they can be decoupled and linearized into the longitudinal and lateral equations. Roll control is a lateral problem and this work is developed to control the roll angle of an aircraft for roll control in order to stabilize the system when an aircraft performs the rolling motion. The roll control system is shown in Fig.1.

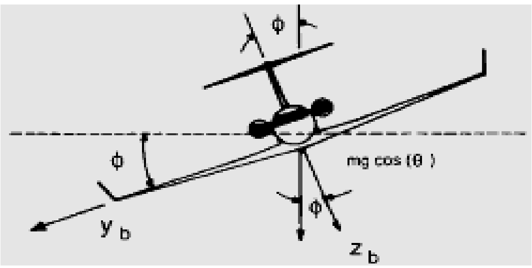

Figure 1: Description of Roll Control System

In this Figure, *Yb* and *Zb* represent the aerodynamic force components; φ and *a*δ represent the orientation of aircraft (roll angle) in the earth-axis system and aileron deflection angle respectively.

Referring to Figure 1, the rigid body equations of motion are obtained from Newton's second law [1]. But, a few assumptions and approximations need to be considered before obtaining the equations of motion. Assume that the aircraft is in steady-cruise at constant altitude and velocity, thus, the thrust and drag cancel out and the lift and weight balance out each other. Also, assume that change in pitch angle does not change the speed of an aircraft under any circumstance. With these assumptions, the lateral directional motion of an aircraft is described by the following kinematic and dynamic differential equations.

$$Y + mgC_{\theta}S_{\theta} = m(\dot{v} + ru - pw)$$

$$L = I_x\dot{p} - I_{xz}\dot{r} + qr(I_z - I_y) - I_{xz}pq$$

$$N = -I_{xz}\dot{p} + I_z\dot{r} + pq(I_y - I_x) + I_{xz}qr \quad \text{---- equ. (1)}$$

Above equations are nonlinear and they can be linearized by using small-disturbance theory. According to small-disturbance theory, all the variables in these equations are replaced by a reference value plus a perturbation or disturbance as given below in equation 2.

For convenience, the reference flight condition is assumed to be symmetric and the propulsive forces are assumed to remain constant. After linearization the following equations are obtained,

$$\begin{aligned}&\left(\frac{d}{dt}-Y_v\right)\Delta v-Y_p\Delta p+(u_0-Y_r)\Delta r-(g\cos\theta_0)\Delta\phi=Y_{\delta r}\Delta\delta_r\\&-L_v\Delta v+\left(\frac{d}{dt}-L_p\right)\Delta p-\left(\frac{I_{xz}}{I_x}\frac{d}{dt}+L_r\right)\Delta r=L_{\delta a}\Delta\delta_a+L_{\delta r}\Delta\delta_r\\&-N_v\Delta v-\left(\frac{I_{xz}}{I_z}\frac{d}{dt}+N_p\right)\Delta p+\left(\frac{d}{dt}-N_r\right)\Delta r=N_{\delta a}\Delta\delta_a+N_{\delta r}\Delta\delta_r\end{aligned}$$ ---- equ.(2)

The lateral directional equations of motion consist of the side force, rolling moment and yawing moment equations of motion. It is sometimes convenient to use the sideslip angle Δβ instead of the side velocity Δ*v*. If the product of inertia *Ixz=0*, the lateral equations of motion can be rearranged and reduced into the state space form in the following manner.

$$\begin{bmatrix}\Delta\dot{\beta}\\\Delta\dot{p}\\\Delta\dot{r}\\\Delta\dot{\phi}\end{bmatrix}=\begin{bmatrix}\frac{Y_\beta}{u_0}&\frac{Y_p}{u_0}&-\left(1-\frac{Y_r}{u_0}\right)&\frac{g\cos\theta_0}{u_0}\\L_\beta&L_p&L_r&0\\N_\beta&N_p&N_r&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}\Delta\beta\\\Delta p\\\Delta r\\\Delta\phi\end{bmatrix}+\begin{bmatrix}0&\frac{Y_{\delta r}}{u_0}\\L_{\delta a}&L_{\delta r}\\N_{\delta a}&N_{\delta r}\\0&0\end{bmatrix}\begin{bmatrix}\Delta\delta_a\\\Delta\delta_r\end{bmatrix}$$ ---- equ.(3)

For this system, the input will be the aileron deflection angle and the output will be the pitch angle. In this study, the data from General Aviation Airplane: NAVION is used in system analysis and modeling.

$$\begin{bmatrix}\Delta\dot{\beta}\\\Delta\dot{p}\\\Delta\dot{r}\\\Delta\dot{\phi}\end{bmatrix}=\begin{bmatrix}-0.254&0&-1&0.183\\-15.969&-8.395&2.19&0\\4.549&-0.349&-0.76&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}\Delta\beta\\\Delta p\\\Delta r\\\Delta\phi\end{bmatrix}+\begin{bmatrix}0\\-28.916\\-0.224\\0\end{bmatrix}[\Delta\delta_a]$$ ---- equ.(4)

Transfer function from aileron deflection angle to roll angle is given by the following equation.

$$\frac{\Delta\phi(s)}{\Delta\delta_a(s)}=\frac{-28.92s^2-29.81s-140.8}{s^4+9.409s^3+14.02s^2+48.5s+0.3979}$$ ---- equ.(5)

IV. Real-time system and modelling

The generic block diagram of real-time flight control system is as shown in Fig. 2. The data signals from 6 different sensors and signal input from pilot are subjected to the controller along with feedback from the aircraft.

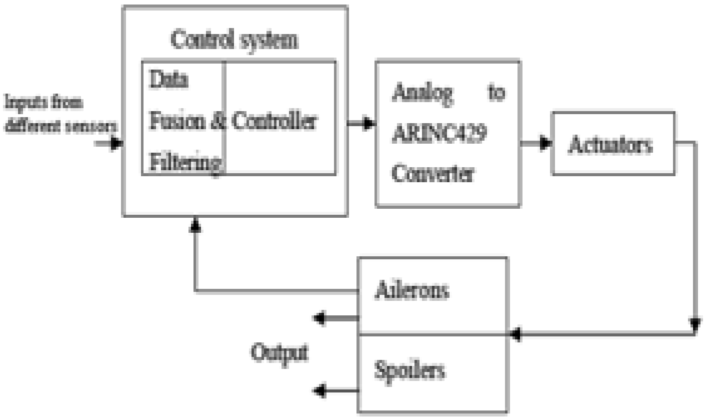

Figure 2: Block Diagram of Roll Control System

Generally an aircraft has three primary control operations called pitch, roll and yaw. The roll action control is considered for the present modeling. The sensed data from 6 different sensors is fused using mixers, limiters and differential amplifiers and is converted to a single analog signal. In this paper the error correction of the resultant data signal is estimated by performing single step test on the process input. The modeling of the PID controller is carried out in MATLAB/ Simulink for the roll action transfer function of equation (5). The PID controller which is modeled is incorporated in the place of controller [6] in the block diagram shown in Fig. 3a.

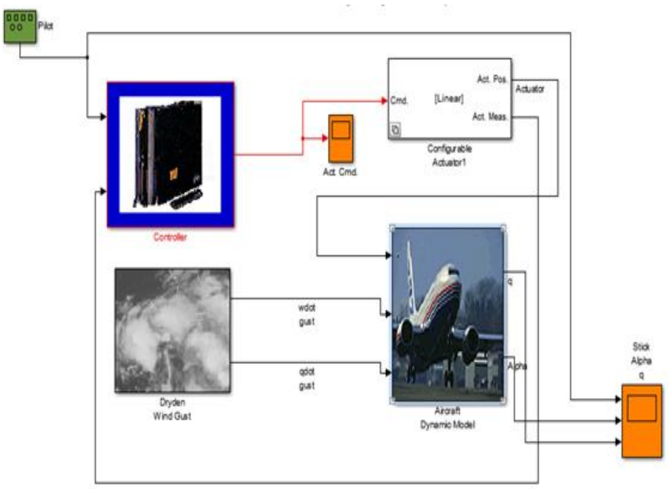

Figure 3a: Block Diagram of Real-time flight control System

The individual units of a real time flight control system are simulated for the equivalent hardware units. The results obtained are compared with LQR and NEM methods [7] and are discussed as follows.

4.1 Modelling of PID Controller

Tthe controller here in the block diagram is PID controller i.e., implemented by MATLAB Simulink. The MATLAB Simulink diagram of PID controller is as shown in Fig.3b.

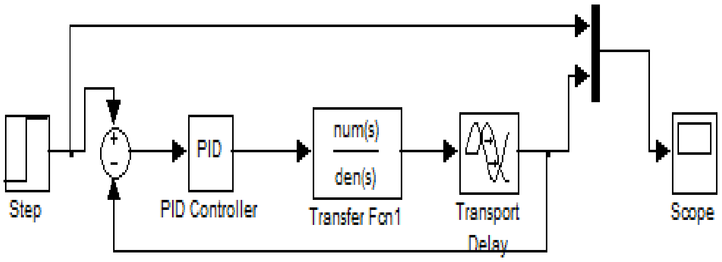

Figure 3b: Simulink model of PID Controller

Step Response of PI Controller

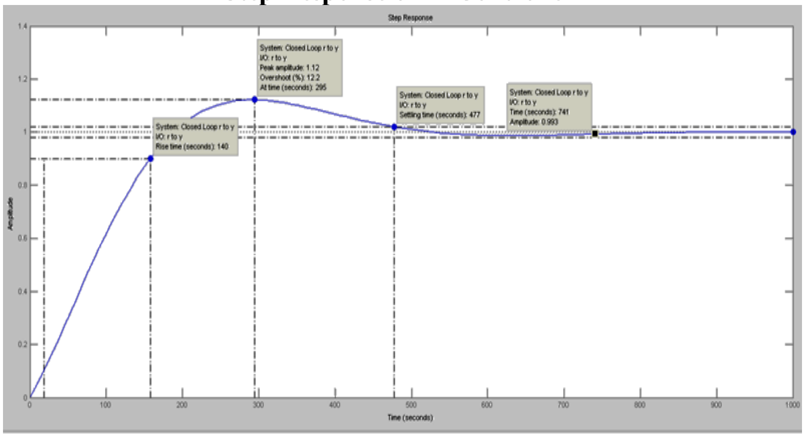

Figure 4: Step response of mathematical model of PI Controller
Tr=140sec, Ts=477sec, Overshoot=12. 2%

Step Response of PD Controller

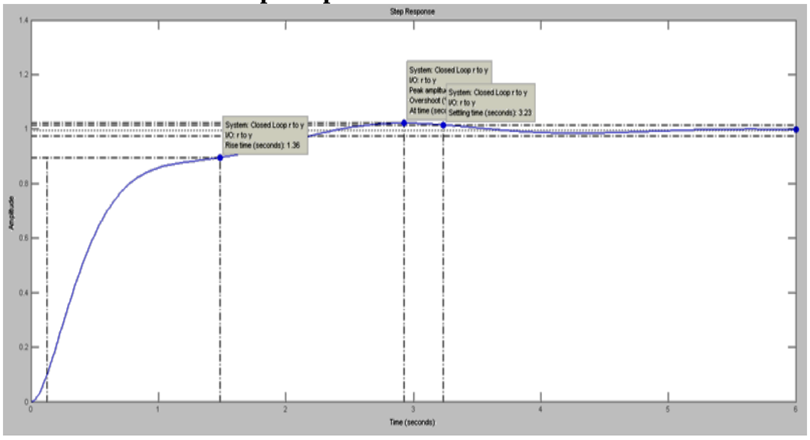

Figure 5: Step response of mathematical model of PD Controller
Tr= 1.36 sec, Ts= 3.23 sec, Overshoot=2.62%

Step Response of PID Controller with Automatic Tuning

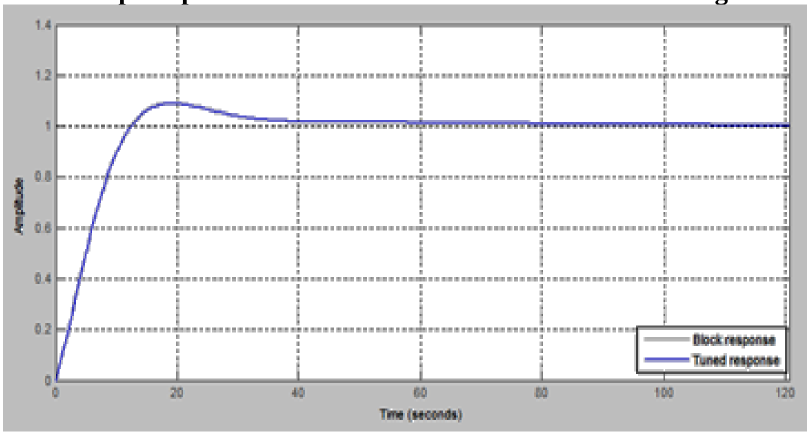

Figure 6: Step response of mathematical model of PID Controller with automatic tuning
Tr = 9 sec, Ts= 39.8 sec, Overshoot=9%

Step Response of PID Controller with Robust Tuning

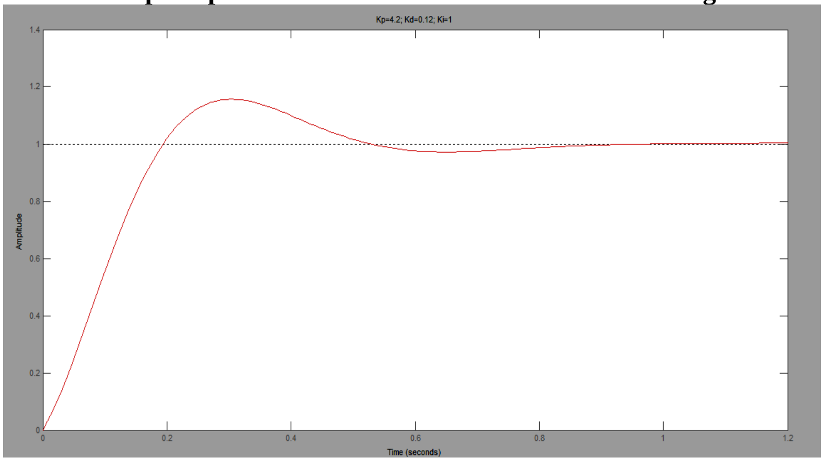

Figure 7: Step response of mathematical model of PID Controller with robust tuning
Tr=0.194 sec, Ts=0.965 sec, Overshoot=16%

Step Response of PID Controller with Ziegler-Nichols (ZN) Tuning

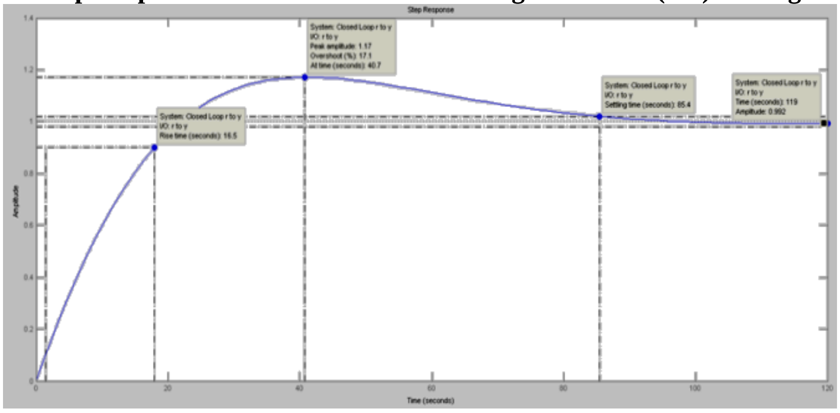

Figure 8: Step response of mathematical model of PID Controller with ZN tuning
Tr=116.5sec, Ts=85.4sec, Overshoot=17.1%

Step Response of PID Controller with IMC Tuning

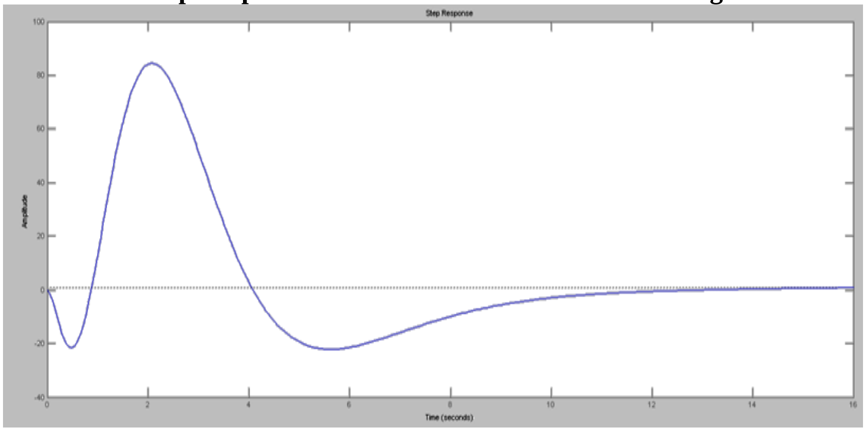

Figure 9: Step response of mathematical model of PID Controller with IMC tuning
Tr =1.7sec, Ts= 13 sec, Overshoot=70%

After implementing the PID controller for different tuning methods, the parameters obtained are no close to the real-time values. Hence there is a need for a non-linear controller like Fuzzy logic controller, which meets the highlighted performance parameters.

4.2 Modeling of fuzzy controller

In auto-pilot aircraft control, the important problem of the system is the need to cope up with the large amount of uncertainties in the data. Fuzzy logic has features, which make it apt in such cases. Unlike classical logic controllers, fuzzy logic controllers are said to be tolerant to uncertainty [9]. This makes easier to implement fuzzy controller to non-linear models. The MATLAB/Simulink model of fuzzy logic controller is as shown in Fig. 10.

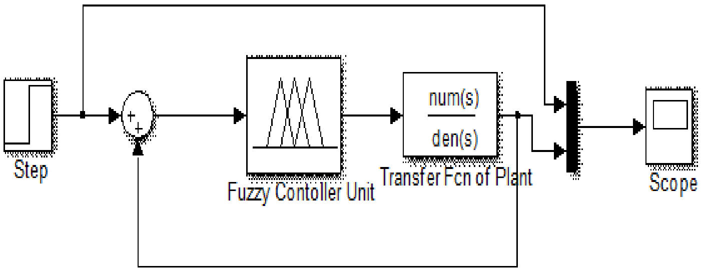

Figure 10: Simulink Model of Fuzzy Logic Controller

The fuzzy logic controller is modelled in Mamdani style because of its simplicity and its compatibility with human decision. The error (e) and derivative of error (de) are considered as inputs. Rules are framed by considering AND as minimum and OR as maximum. The result obtained for this is discussed as follows.

Step Response of PID Controller with Fuzzy Logic Controller

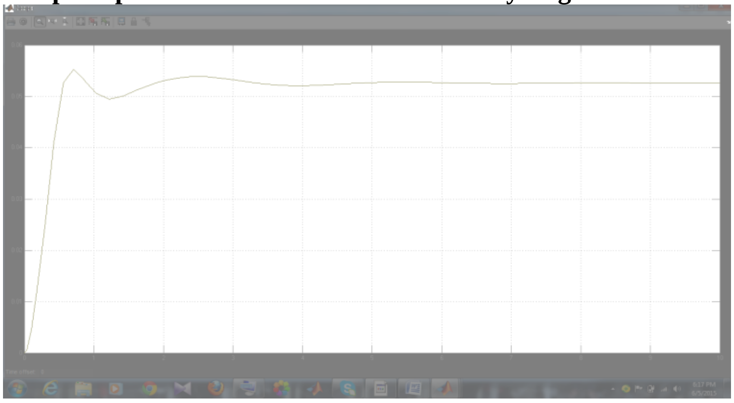

Figure 11: Step response of mathematical model of Fuzzy Logic Controller
Tr = 0. 557 sec, Ts= 5. 5 sec, Overshoot=0%

The better advantage of PID control and fuzzy control are achieved by adequately integrating these two techniques. The integration is done by tuning the PID parameters using fuzzy interface which provides non-linear mapping from the error and derivative of error to PID parameters. By the integration, higher static precision and faster dynamic response can be achieved. The block diagram of fuzzy-PID controller is given in Fig.5. The MATLAB/Simulink model of integrated fuzzy-PID controller is as shown in Fig. 12.

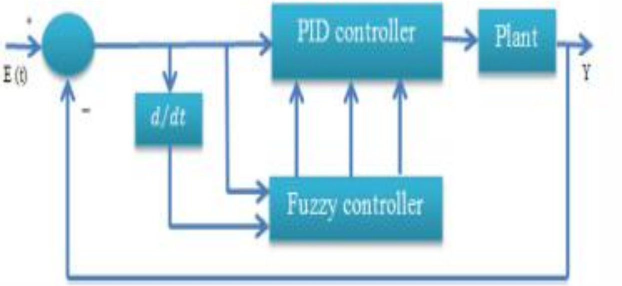

Figure 12: Block Diagram of Fuzzy-PID Controller
The MATLAB/Simulink model of integrated fuzzy-PID controller is as shown in Fig. 13.

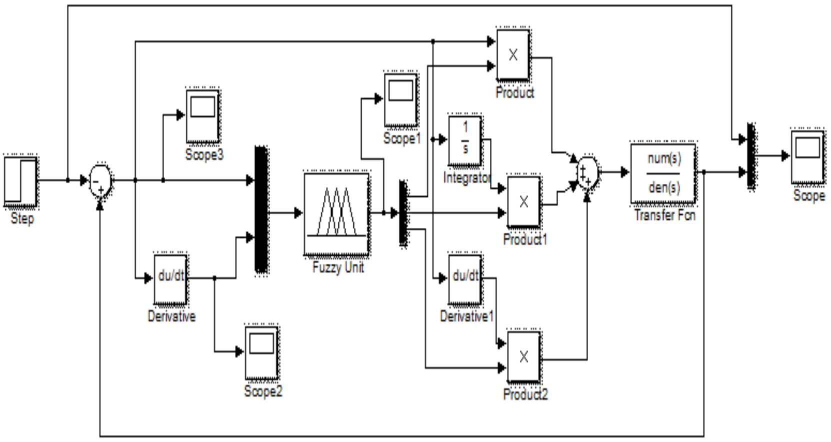

Figure 13: MATLAB/Simulink Model of Fuzzy-PID Controller

The integrated fuzzy-PID controller is a self-tuning fuzzy-PID controller. The fuzzy interface system [FIS] is used to tune the parameters of Kp, Ki, Kd according to error (e) and derivative of error (de). The self-tuning feature guarantees the best dynamic performance for a wide variation of system parameters. The FIS is modeled in Mamdani style with two inputs, e and de and three outputs Kp, Ki, Kd by framing 36 rules. The results are discussed as follows.

Step Response of PID Controller with Fuzzy-PID Controller

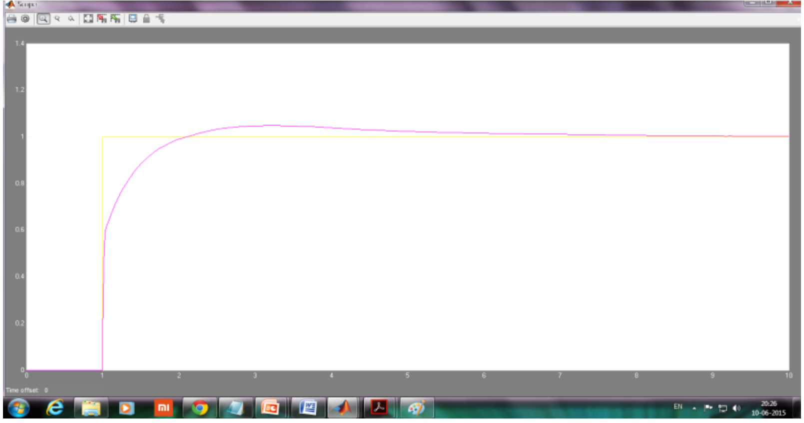

Figure 14: Step response of mathematical model of Fuzzy-PID Controller
Tr = 0. 5 sec, Ts= 7sec, Overshoot=4%

But, the response time and the other performance parameters obtained are not satisfactory which don’t match with the real-time values. Hence, the intelligent search algorithm, **Genetic Algorithm (GA)** is applied for the tuning of the modeled adaptive PID controller

4.3 Genetic Algorithm

Many heuristic algorithms have evolved to solve the optimization problems. One of the best and simplest heuristic search algorithms is Genetic Algorithm, based on the evolutionary ideas of natural selection and genetics. The basic principle of genetic algorithm follow the rule lay down by Charles Darwin of “Survival of the fittest”. Genetic Algorithm [GA] is more robust unlike other algorithms [13]. The main advantage of GA is, a system implemented with GA doesn’t break easily even if there are any slight changes in the inputs (or) in the presence of reasonable noise. So, this GA is used for optimizing the co-efficient values of the modeled PID controller and the resultant controller is named as PID-GA Controller as shown in the Fig.15.

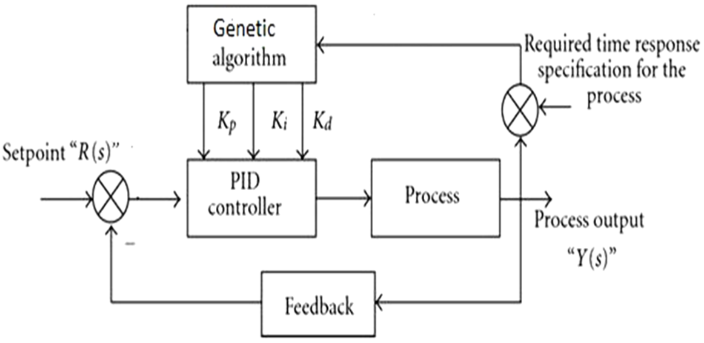

Figure 15: PID Controller with Genetic Algorithm Optimization

The following is the flow chart of GA which is implemented and is shown in Fig.16. Here, in this work, the initial population is considered to be 100. While implementing GA, it is required to set the values of upper and lower bounds between which optimized values will be obtained. The selection of these bounds is also an important and critical task. For this, the P, I, D co-efficient values obtained from the Z-N method are used. The nearest values of these co-efficients are considered as lower and upper bounds. In the next step after the bound selection, fitness function of the PID controller is considered for evaluation and rank wise fitness scaling is done. We can consider different forms of mutation like Gaussian, uniform, constraint dependent, custom etc., In this paper uniform mutation process is considered. After setting mutation, crossover process is to be selected. From scattered, single point, two-point, intermediate, heuristic, arithmetic, custom methods, scattered method of cross over is taken and the optimization process is evoked. The above set values are considered and GA is implemented for the modeled PID controller. Complete model simulation is carried through MATLAB/Simulink. The simulation results of PID-GA controller provides us the optimized co-efficients required for the PID controller. The P, I, D co-efficients obtained are Kp=4.116, Ki=0.878, Kd=1. The PID controller implemented with the obtained values gives us better performance in terms of all specified parameters like rise time, settling time and overshoot. The results of this are discussed in results and discussion section. The final PID-GA controller is one of the robust and efficient controllers modeled to correct/minimize the error in the input signal effectively.

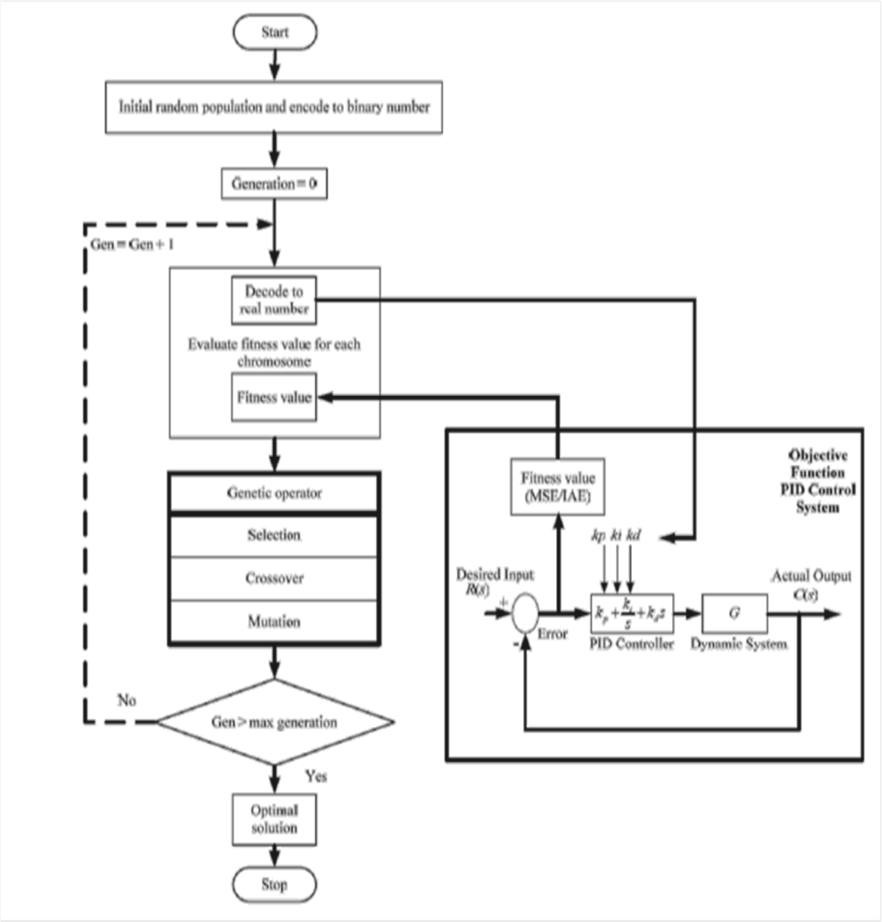

Figure 16: Flow chart of Genetic Algorithm with PID controller

Step Response of PID Controller with GA Optimization

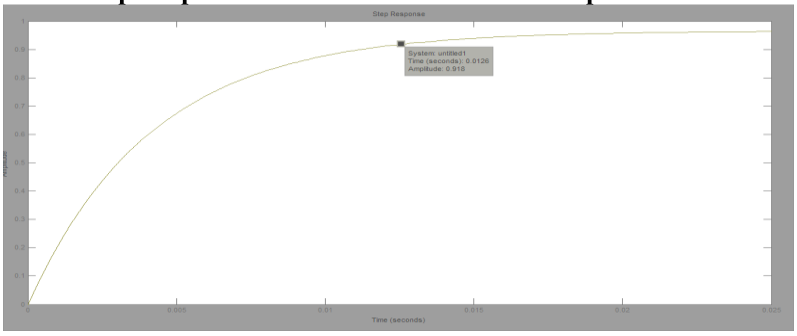

Figure 17: Step response of mathematical model of PID Controller with GA Optimization
Tr = 0.01 sec, Ts= 0.9 sec, Overshoot = 0%

V. Results and Discussion:

By considering the variation in different conditions like noise, pressure, temperature, altitude, angle of attack, roll rate etc., of an aircraft, the PID controller is modeled and simulated to control the roll control action of an aircraft. Before modeling the PID, different combinations like PI, PD are also modeled and simulated [6]. The performance analysis of these methods for the system is simulated in MATLAB/ Simulink.

Initially the PID controller is tuned through auto-tuning and robust tuning methods [8][10]. Further to improve the performance of PID controller the two classical methods 1. Ziegler-Nichols (Z-N) method and 2. IMC tuning are applied [3]. But, the response time and the other performance parameters obtained are not satisfactory. In order to achieve better performance, fuzzy and fuzzy-PID controllers are introduced with the plant. The response of the system with the plant is stable with increased ringing and settling time and overshoot. Hence, the PID-GA controller is implemented which gives the better optimized values for P, I, D co-efficients. All the comparisons of parameters like rise time, settling time and overshoot [9] for different methods are depicted in Table 1. The performance parameters of various tuning methods and combinations of PID are discussed as follows.

By observing all the simulation results, a comparison table of the transient performance parameters is given in Table1.

TABLE 1: COMPARISON OF DIFFERENT PARAMETERS

Algorithm	**Rise time (sec)**	**Setting time (sec)**	**Peak Overshoot (%)**
PI	140	477	12. 2
PD	1. 36	3. 2 3	2. 6 2
PID(Automatic)	9	39.8	9
PID(Robust)	0.194	0.965	16
PID-ZN	16. 5	85. 4	17. 1
PID-GA	***0.0108***	***0.9***	***0***
IMC	1.7	13	70
FLC	0. 557	5. 5	12
Fuzzy-PID	0. 5	6	4
LQR	0.29	0.365	2.8
NEM(Non-linear Energy Method)	20	30	0

From Table 1 it is observed that the rise-time, settling time and overshoot are optimum for PID controller with genetic algorithm optimization. The response is achieved with minimum steady state error in GA tuning within few milliseconds.

VI. Conclusion

In this paper, the proposed adaptive controller for an aircraft roll control system was designed in MATLAB/ Simulink environment. PID controllers with different combinations of P, I, D are modeled for different tuning methods. An intelligent fuzzy controller is also modeled for the non-linear system. For better precision and dynamic response, integrated fuzzy-PID controller is also modeled. The results obtained are compared for different performance parameters like rise time, settling time, overshoot. Obtained simulation results show that PID controller with Genetic Algorithm Optimization takes only 1msec for the response with considerable undershoot in comparison to other tuning methods of PID controller and this controller increases the speed of the time response very quickly.

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