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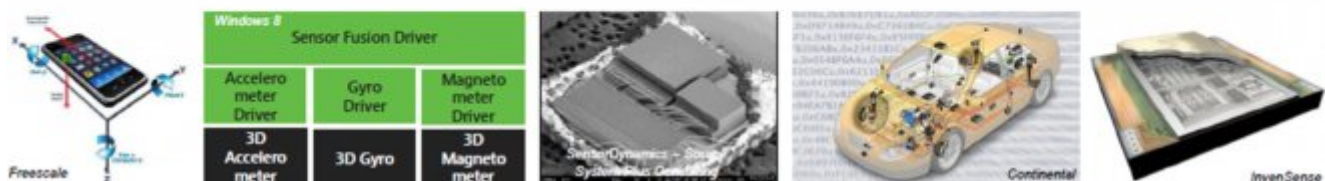
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Lateral Control of Aircraft, Considering the Cross-coupling Effect of Yaw and Roll on Each-other Using Fuzzy Logic

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Abstract: In this paper, we explore fuzzy logic based approach for lateral control of aircrafts.. Here the effect of roll on yaw and that of yaw on roll is taken into account. So the system will have greater accuracy and efficiency than the application of two separate controllers. This design will significantly reduce instability and increases maneuverability, as compared to existing control systems.

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Keywords: Aircraft, Fuzzy logic controller, Roll, Yaw.

1. Introduction

The development of autopilots closely followed the successful development of powered man-carrying airplane by the Wright brothers [1]. The first automatic flight controller in the world is designed by the Sperry brothers in 1912. The Sperry brothers developed an autopilot that is sensitive to the movements of an aircraft. When an aircraft deviated from a particular flight route, this autopilot adjusted the pitch, roll and heading angles of an aircraft. Then, in 1914, the Sperry brothers demonstrated this autopilot at the Paris air-show. To demonstrate the effectiveness of their design, Lawrence Sperry trimmed his airplane for straight and level flight and then engaged the autopilot [1]. Since then, the fast advancement of high performance military, commercial and general aviation aircraft design has required the development of many technologies; these are aerodynamics, structures, materials, propulsion and flight controls [2]. Currently, the aircraft design relies heavily on automatic control systems to monitor and control many of the aircraft subsystems [2]. Therefore, the development of automatic control systems has played an important role in the growth of civil and military aviation [1]. Modern aircrafts are much more complex and includes a variety of automatic control system.

Generally, an aircraft is controlled by three main surfaces. These are elevator, rudder and ailerons. Pitch control can be achieved by changing the lift on either a forward or aft control surface. If a flap is used, the flapped portion of the tail surface is called an elevator. Yaw control is achieved by deflecting a flap on the vertical tail called the rudder and roll control can be achieved by deflecting small flaps located outboard toward the wing tips in a differential manner [1]. These flaps are called ailerons. Elevator, rudder and ailerons are depicted in Fig. 1.

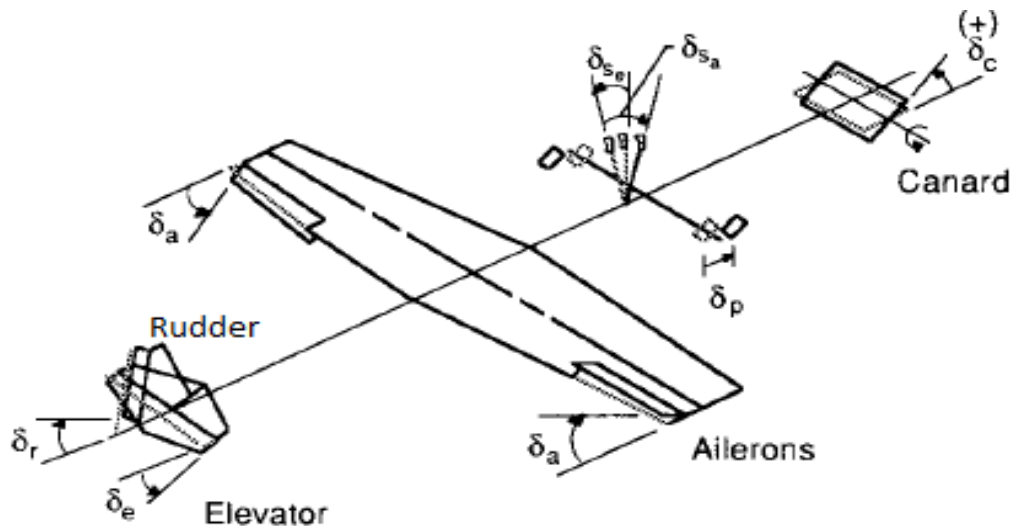


Fig. 1. Aerodynamic controls of an aircraft [1].

In this study, an autopilot is designed to control the yaw angle and roll angle of an aircraft. In aircraft modeling phase, the aerodynamic forces (lift and drag) as well as the aircraft's inertia are taken into account [4]. This is a third order, nonlinear system which is linearized about the operating point [4]. An intelligent controller (FLC) is developed for the lateral control of an aircraft system. Performance of the controller is analyzed with respect to the desired yaw and roll angles.

2. System Modeling

2.1. Modelling of Lateral Control System

Flight control system has been designed using mathematical models of the aircraft linearized at various flight condition parameters varied with the flight operating conditions. This work is developed to control the roll and yaw angles of an aircraft in order to stabilize the system. The importance of this work is that here the effect of roll on yaw and that of yaw on roll is taken into account. So the system will have greater accuracy and efficiency than the application of two separate controllers. The aircraft being considered in this work is a standard NAVION Transport aircraft [1]. The specifications are given below:

General equations for aircrafts [1]:

$$\begin{aligned}
 Y_{\beta} &= \frac{QS C_{Y\beta}}{m} (\text{ft}/s^2) & N_{\beta} &= \frac{QS b C_{n\beta}}{I_z} (s^{-2}) & L_{\beta} &= \frac{QS b C_{l\beta}}{I_x} (s^{-2}) \\
 Y_p &= \frac{QS b C_{Yp}}{2m u_0} (\text{ft}/s) & N_p &= \frac{QS b^2 C_{np}}{2I_z u_0} (s^{-1}) & L_p &= \frac{QS b^2 C_{lp}}{2I_x u_0} (s^{-1})
 \end{aligned}$$

$$\begin{aligned}
 Y_r &= \frac{Q S b C_{Yr}}{2 m u_0} (\text{ft/s}) & N_r &= \frac{Q S b^2 C_{Nr}}{2 I_x u_0} (s^{-1}) & L_r &= \frac{Q S b^2 C_{Lr}}{2 I_x u_0} (s^{-1}) \\
 Y_{\delta\alpha} &= \frac{Q S C_{Y\delta\alpha}}{m} (\text{ft/s}^2) & Y_{\delta r} &= \frac{Q S C_{Y\delta r}}{m} (\text{ft/s}^2) & L_{\delta\alpha} &= \frac{Q S b C_{L\delta\alpha}}{I_x} (s^{-2}) \\
 N_{\delta\alpha} &= \frac{Q S b C_{N\delta\alpha}}{I_z} (s^{-2}) & N_{\delta r} &= \frac{Q S b C_{N\delta r}}{I_z} (s^{-2}) & L_{\delta r} &= \frac{Q S b C_{L\delta r}}{I_x} (s^{-2})
 \end{aligned}$$

Table 1. The lateral directional derivatives stability parameters [3].

General Aviation Airplane: NAVION	Y-Force Derivatives	Yawing Moment Derivatives	Rolling Moment Derivatives
Pitching Velocities	$Y_r = 0.254$	$N_r = 0.025$	$L_r = -0.091$
Side Slip Angle	$Y_{\beta} = -44.665$	$N_{\beta} = 4.549$	$L_{\beta} = -15.969$
Rolling Rate	$Y_p = 0$	$N_p = -0.349$	$L_p = -0.395$
Yawing Rate	$Y_r = 0$	$N_r = -0.76$	$L_r = 2.19$
Rudder Deflection	$Y_{\delta r} = 12.483$	$N_{\delta r} = -4.613$	$L_{\delta r} = 23.09$
Aileron Deflection	$Y_{\delta\alpha} = 0$	$N_{\delta\alpha} = -0.224$	$L_{\delta\alpha} = -28.916$

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 [5]. Yaw and Roll controls are lateral problem and this work is developed to control the yaw and roll angles of an aircraft for yaw and roll control in order to stabilize the system when an aircraft performs the yawing and rolling motions. The control surfaces of aircraft are shown in Fig. 2.

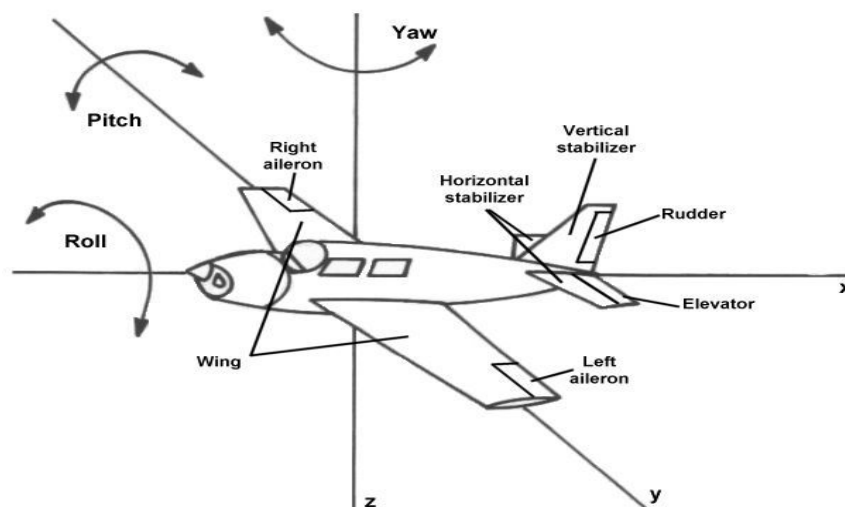


Fig. 2. Yaw, Roll & Pitch motion of Aircraft [6].

The forces, moments and velocity components in the body fixed frame of an aircraft system are shown in Fig. 3 where L , M and N represent the aerodynamic moment components; the term p , q and r represent the angular rates components of roll, pitch and yaw axis and the term u , v and w represent the velocity components of roll, pitch and yaw axis.

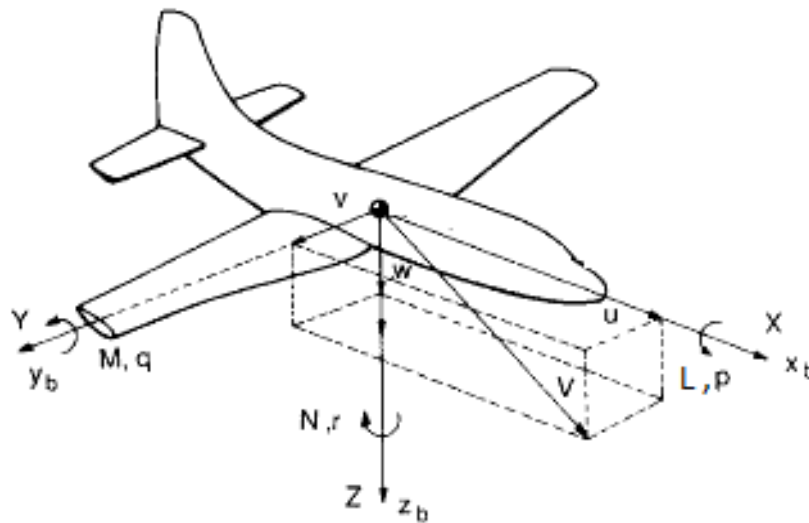


Fig. 3. Definition of forces, moments and velocity components in a body fixed frame [1].

Referring to Fig. 3, the rigid body equations of motion are obtained from Newton's second law, see [1]. But, a few assumption and approximation 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 [5]. Under these assumptions, the lateral directional motion of an aircraft is well described by the following kinematic and dynamic differential equations.

$$Y + mg C_{\theta} S_{\theta} = m \left(\frac{dv}{dt} + ru - pw \right) \quad (1)$$

$$L = I_x \frac{dp}{dt} - I_{xz} \frac{dr}{dt} + qr(I_x - I_y) - I_{xz} pq \quad (2)$$

$$N = -I_{xz} \frac{dp}{dt} + I_z \frac{dr}{dt} + pq(I_y - I_x) - I_{xz} qr \quad (3)$$

Equation (1), (2) and (3) are nonlinear and they can be linearized by using small-disturbance theory. According to small-disturbance theory, all the variables in the equation (1), (2) and (3) are replaced by a reference value plus a perturbation or disturbance, as given in equation (4).

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

$$p = p_0 + \Delta p; q = q_0 + \Delta q; Y = Y_0 + \Delta Y$$

$$r = r_0 + \Delta r; L = L_0 + \Delta L; M = M_0 + \Delta M$$

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

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

$$v = p = q = r = \dot{\phi} = \psi = 0 \quad (5)$$

After linearization the following equations (6), (7) and (8) are obtained, see [1].

$$\left(\frac{d}{dt} - Y_V\right) \Delta v - Y_P \Delta p + (u_0 - Y_r) \Delta r - (g \cos \theta_0) \Delta \phi = Y_{\delta_r} \Delta \delta_r \quad (6)$$

$$-L_V \Delta v + \left(\frac{d}{dt} - L_P\right) \Delta p - \left(\frac{L_{xz} \frac{d}{dt} + L_r}{I_x \frac{d}{dt}} + L_r\right) \Delta r = L_{\delta_\alpha} \Delta \delta_\alpha + L_{\delta_r} \Delta \delta_r \quad (7)$$

$$-N_V \Delta v + \left(\frac{d}{dt} - N_r\right) \Delta r - \left(\frac{L_{xz} \frac{d}{dt} + N_P}{I_z \frac{d}{dt}} + N_P\right) \Delta p = N_{\delta_\alpha} \Delta \delta_\alpha + N_{\delta_r} \Delta \delta_r \quad (8)$$

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 $\Delta\beta$ instead of the side velocity Δv . These two quantities are related to each other in the following way:

$$\Delta\beta \approx \tan^{-1} \frac{\Delta v}{u_0} = \frac{\Delta v}{u_0} \quad (9)$$

Using this relationship and if the product of inertia $I_{xz}=0$, the lateral equations of motion can be rearranged and reduced into the state space form in the following manner.

$$\begin{bmatrix} \Delta\beta^s \\ \Delta p^s \\ \Delta r^s \\ \Delta\phi^s \end{bmatrix} = \begin{bmatrix} \frac{Y_\beta}{u_0} & \frac{Y_r}{u_0} & -(1 - \frac{Y_r}{u_0}) & \frac{g \cos \theta_0}{u_0} \\ L_\beta & L_P & L_r & 0 \\ N_\beta & N_P & N_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} + \begin{bmatrix} 0 & \frac{Y_{\delta_\alpha}}{u_0} \\ L_{\delta_\alpha} & L_{\delta_r} \\ N_{\delta_\alpha} & N_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_\alpha \\ \Delta\delta_r \end{bmatrix} \quad (10)$$

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 NAVION Transport [1] is used in system analysis and modeling. The lateral directional derivatives stability parameters for this airplane are given in Table I. Before finding transfer function, let's plug in numerical value given Table I by using equation (10).

2.2. Yaw Transfer Function

This section presents the yaw control for yaw angle of an aircraft system. So, the aileron deflection given in equation (10) is not used.

$$\begin{bmatrix} \Delta\beta^s \\ \Delta p^s \\ \Delta r^s \\ \Delta\phi^s \end{bmatrix} = \begin{bmatrix} -0.254 & 0 & -1 & 0.183 \\ -15.969 & -8.395 & 2.19 & 0 \\ 4.549 & -0.349 & -0.76 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} + \begin{bmatrix} 0 \\ 23.09 \\ -4.613 \\ 0 \end{bmatrix} [\Delta\delta_r] \quad (11)$$

Transfer function from rudder deflection angle to yaw angle is given the following equation (12)

$$\frac{\Delta\phi(s)}{\Delta\delta_r(s)} = \frac{-4.6130 S^3 - 47.9562 S^2 - 11.8833 S + 5.7410}{S^4 + 9.4090 S^3 + 14.0189 S^2 + 48.4991 S + 0.3979} \quad (12)$$

2.3. Roll Transfer Function

$$\begin{bmatrix} \Delta\beta^r \\ \Delta p^r \\ \Delta r^r \\ \Delta\phi^r \end{bmatrix} = \begin{bmatrix} -0.254 & 0 & -1 & 0.183 \\ -15.969 & -8.395 & 2.19 & 0 \\ 4.549 & -0.349 & -0.76 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\beta \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} + \begin{bmatrix} 0 \\ -28.916 \\ -0.224 \\ 0 \end{bmatrix} [\Delta\delta_a] \quad (13)$$

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

$$\frac{\Delta\phi(s)}{\Delta\delta_r(s)} = \frac{-28.92S^2 - 29.81S - 140.8}{S^4 + 9.4090S^3 + 14.0189S^2 + 48.5S + 0.3979} \quad (14)$$

3. Design Process of Proposed Controller

3.1. Fuzzy Logic Controller (FLC) for Yaw Control

In most research literature, a fuzzy controller system is commonly defined as a system that emulates a human expert. In this case, the knowledge of the human operator would be put in the form of a set of fuzzy linguistic rules. These rules would produce an approximate decision in the same manner a human would do. The fuzzy controller is composed of four elements. These are fuzzification, rule base, inference mechanism and defuzzification. A block diagram of a fuzzy control system is shown in Fig. 4.

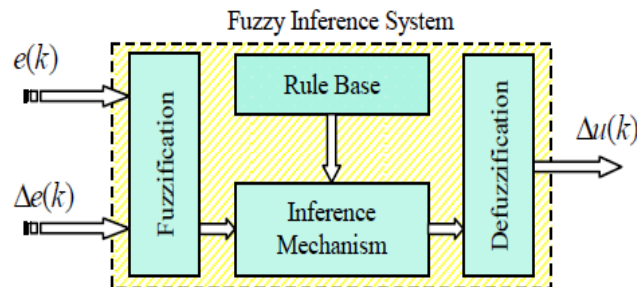


Fig. 4. The basic structure of fuzzy logic based controller [3].

In Fig. 5, the values of error ($e(k)$) and its change ($\Delta e(k)$) occurring during the operation of the system form the crisp inputs of the system. These two inputs defined as in (16) and (17).

$$e(k) = r(k) - y(k) \quad (16)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (17)$$

$r(k)$, $y(k)$ and k are expressed as the reference input, the actual output of the system and the sampling step respectively. These crisp inputs $e(k)$ and $\Delta e(k)$ are converted to fuzzy membership value on the fuzzy subsets negative big (NB), negative small (NS), zero (ZZ), positive small (PS), positive big (PB) etc. The input "Error" consists of the following seven membership functions :- Big Negative Error (BN): Negative Error (N): Small Negative Error (SN): No Error (Z): Small Positive Error (SP): Small Positive Error (P) Big Positive Error (BP).

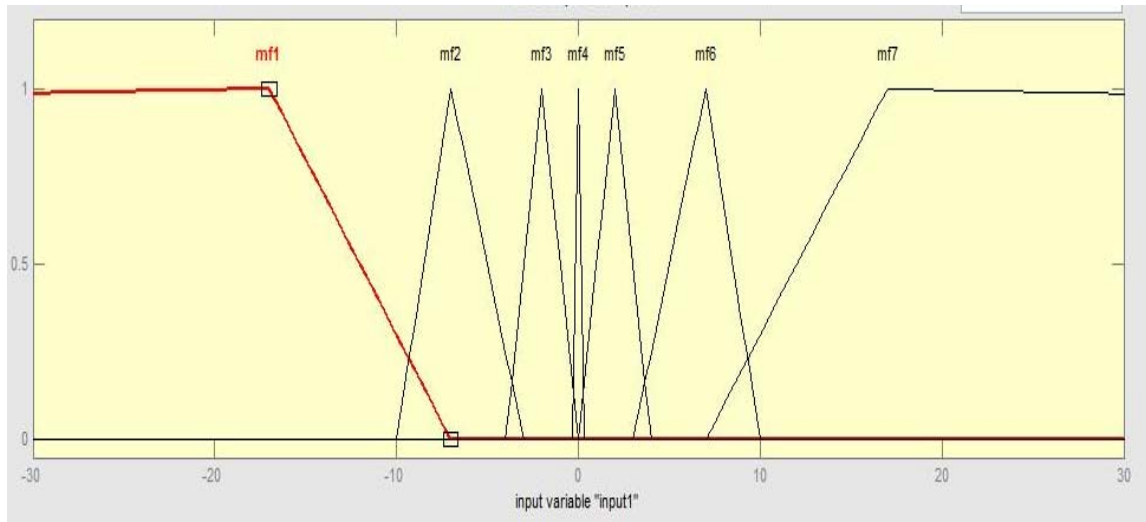


Fig. 5. Error membership functions.

The “Rate of Error” input (Fig. 6), which represents the rate of the error input, consists of five membership functions. Big Negative (BN): Small Negative (NE): Zero Acceleration (ZR): Small Positive (PE): Big Positive (BP).

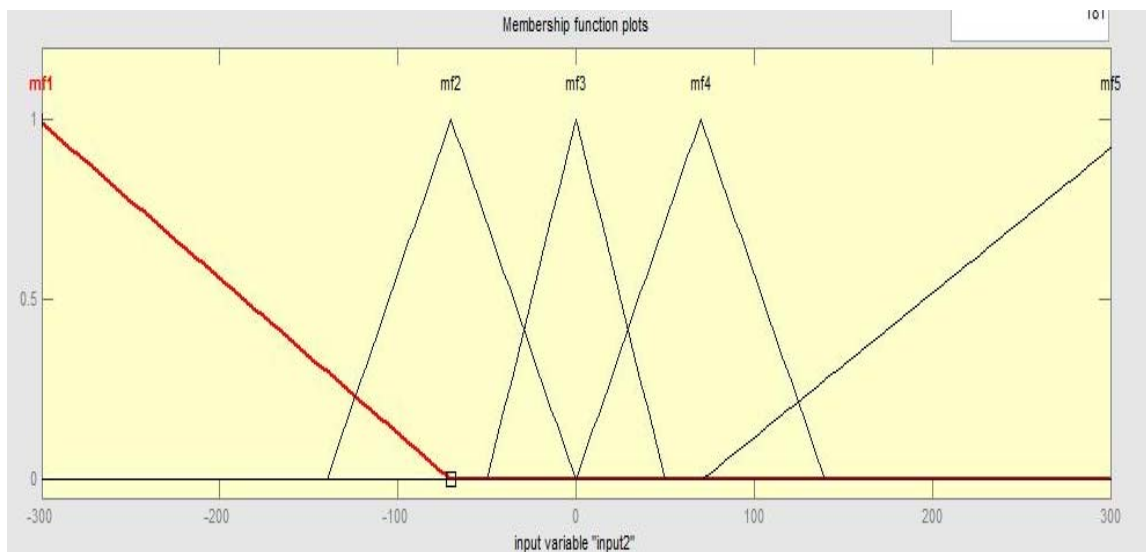


Fig. 6. Rate of error membership functions.

The output of the system (Fig. 7) consists of seven membership functions as:-Big Negative Angle (BNT), Normal Negative Angle (NNT), Negative Angle (NT), Zero Thrust (ZT): Positive Angle (PT): Normal Positive Angle (NPT), Big Positive Angle (BPT).

This fuzzy membership values are used in the rule base in order to execute the related rules so that an output can be generated. A rule base consists of a data table which includes information related to the system. A fuzzy control that has thirty-five rules is realized. These rules have been utilized in designing the controller and the rules are defined in Table 2.

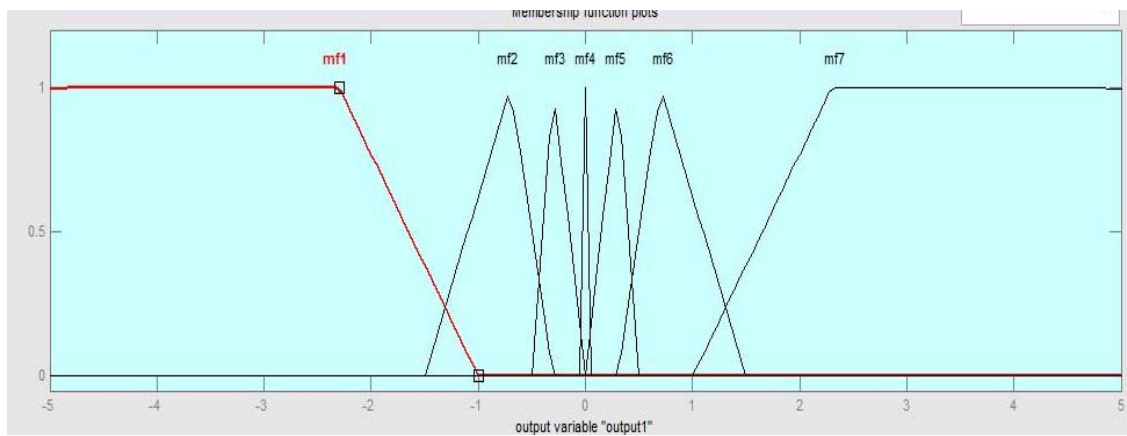


Fig. 7. Output membership functions.

Table 2. The Fuzzy rule base.

INPUTS	BN	NE	ZR	PE	BP
BN	BNT	NNT	NNT	NT	ZT
N	NNT	NT	NT	ZT	PT
SN	NNT	NT	ZT	ZT	PT
Z	NT	NT	ZT	PT	PT
SP	NT	NT	ZT	PT	PT
P	NT	ZT	ZT	PT	NPT
BP	NT	ZT	PT	PT	NPT

An inference mechanism emulates the expert’s decision making in interpreting and applying knowledge about how best to control the plant. A defuzzification interface converts the conclusions of the inference mechanism into the crisp inputs for the process.

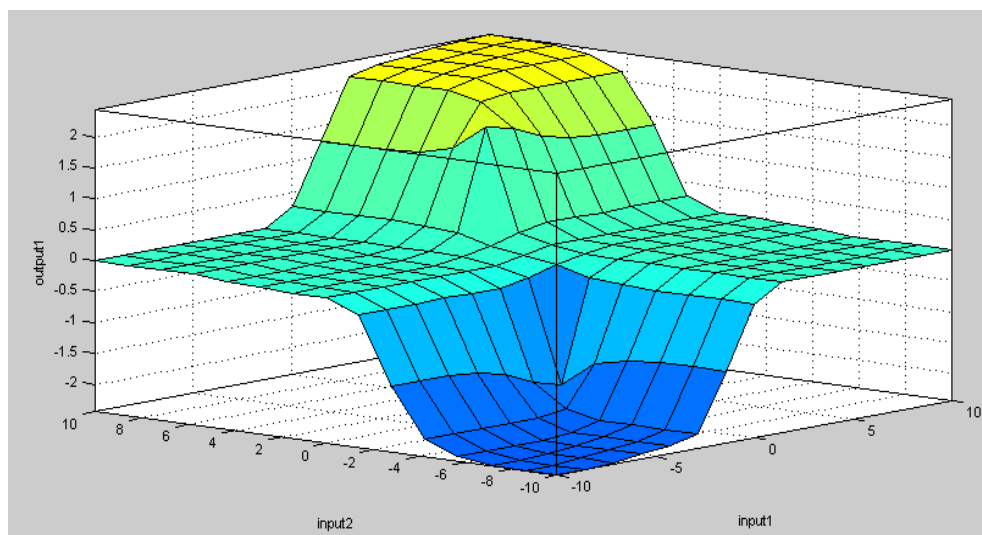


Fig. 8. The rule surface generated.

3.2. Fuzzy Logic Controller (FLC) for Roll Control

The crisp inputs $e(k)$ and $\Delta e(k)$ are converted to fuzzy membership value on the fuzzy subsets negative big (NB), negative small (NS), zero (ZZ), positive small (PS), positive big (PB) etc. The input “Error” (Fig. 9) consists of the following five membership functions Big Negative Error (NB), Small Negative Error (NS.), No Error (ZZ.), Small Positive Error (PS). Big Positive Error (PB).

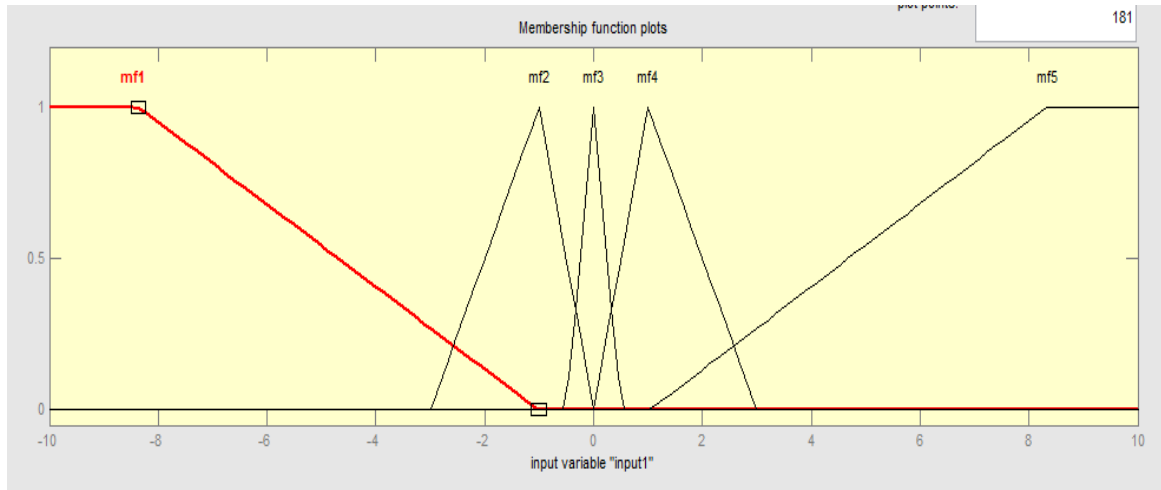


Fig. 9. Error membership functions.

The “Rate of Error” input (Fig. 10), which represents the rate of the error input, consists of five membership functions. Big Negative (NB): Small Negative (NS): Zero Acceleration (ZZ) Small Positive (PS): Big Positive (PB)

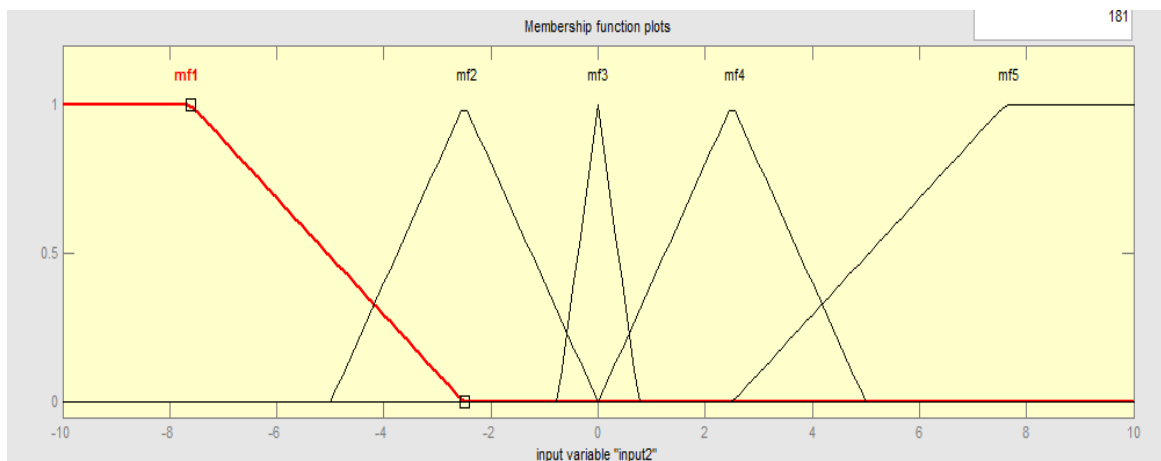


Fig. 10. Rate of error membership functions.

The output of the system (Fig. 11) consists of seven membership functions as:- Big Negative Angle (NB): Small Negative Angle (NS), Zero Thrust (ZZ): Small Positive Angle (PS): Big Positive Angle (PB).

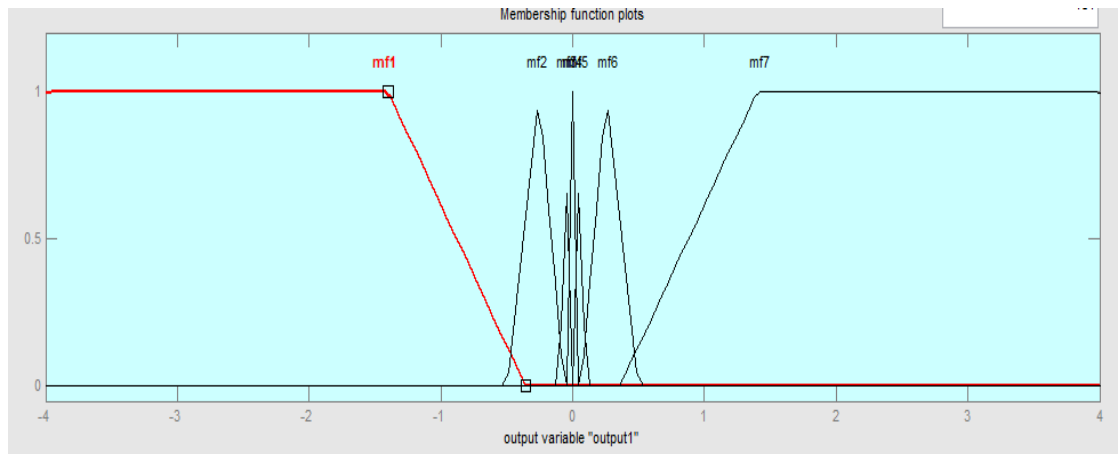


Fig. 11. Output membership functions.

This fuzzy membership values are used in the rule base in order to execute the related rules so that an output can be generated. A rule base consists of a data table which includes information related to the system. A fuzzy control that has thirty-five rules is realized. These rules have been utilized in designing the controller and the rules are defined in Table 3.

Table 3.The Fuzzy rule base.

INPUTS	NB	NS	ZZ	PS	PB
NB	NB	NB	NS	NS	ZZ
NS	NB	NS	NS	ZZ	PS
ZZ	NS	NS	ZZ	PS	PS
PS	NS	ZZ	PS	PS	PB
PB	ZZ	PS	PS	PB	PB

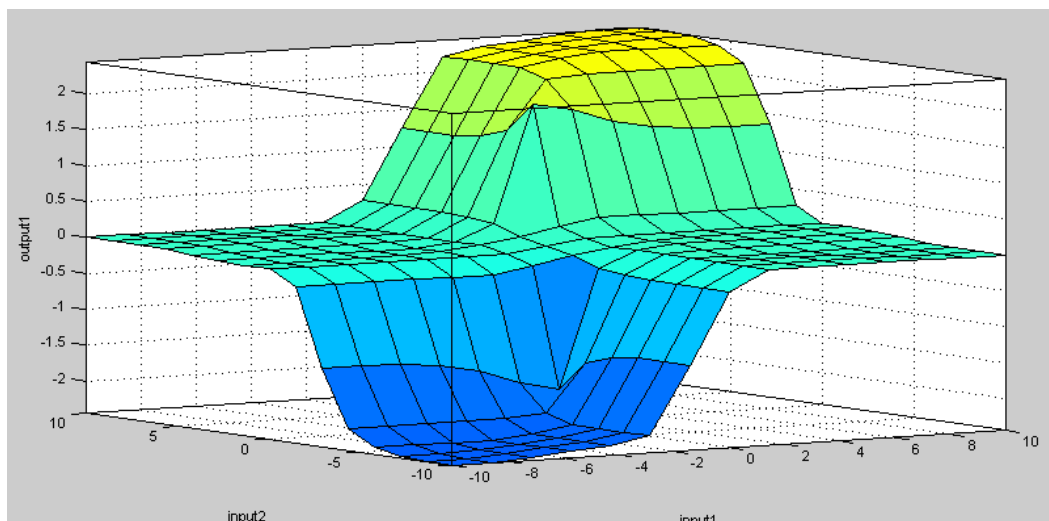


Fig. 12. The rule surface generated.

An inference mechanism emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant. A defuzzification interface converts the conclusions of the inference mechanism into the crisp inputs for the process.

4. Application and Results

An aircraft lateral control system is simulated using FLC and the related simulation results are presented and discussed. Matlab/Simulink model block diagram of this system is shown in Figs. 13 and 14.

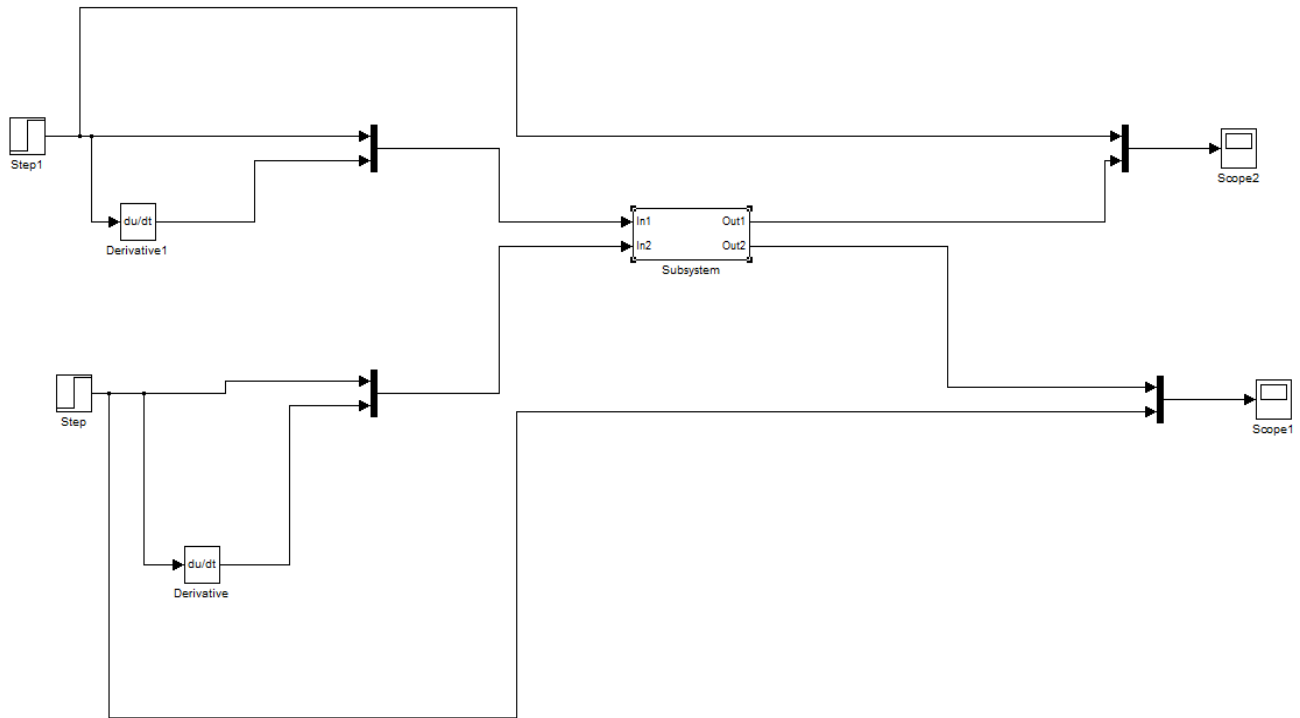


Fig. 13. Matlab/Simulink model for the roll control system.

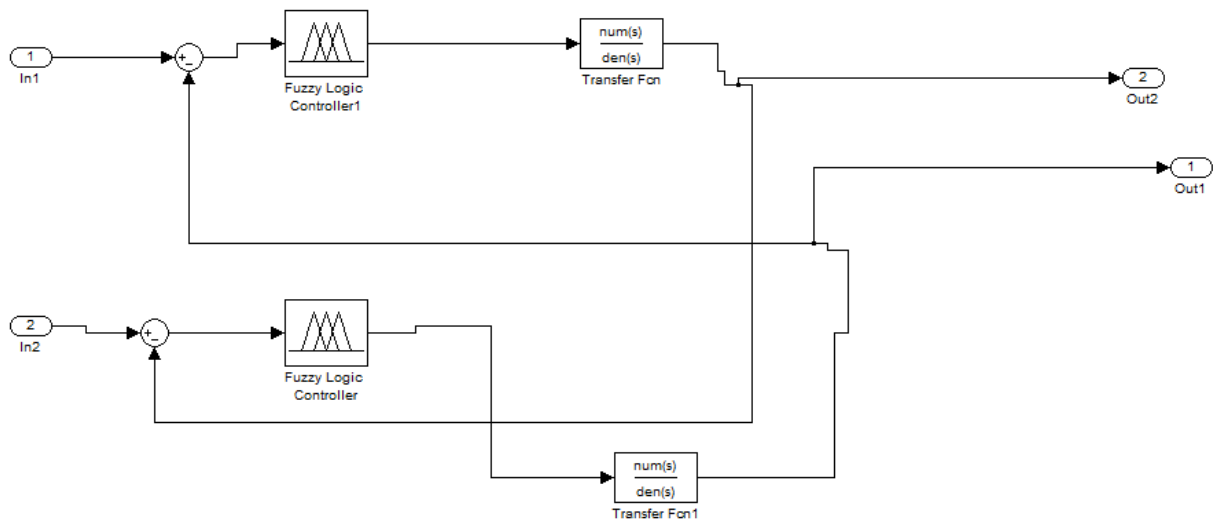


Fig. 14. Sub system for lateral controller.

In this system we had taken the cross-coupling effect of yaw and roll on each other. Instead of deriving the cross-coupled transfer function, Matlab/Simulink blocks are interconnected to get the required cross coupling.

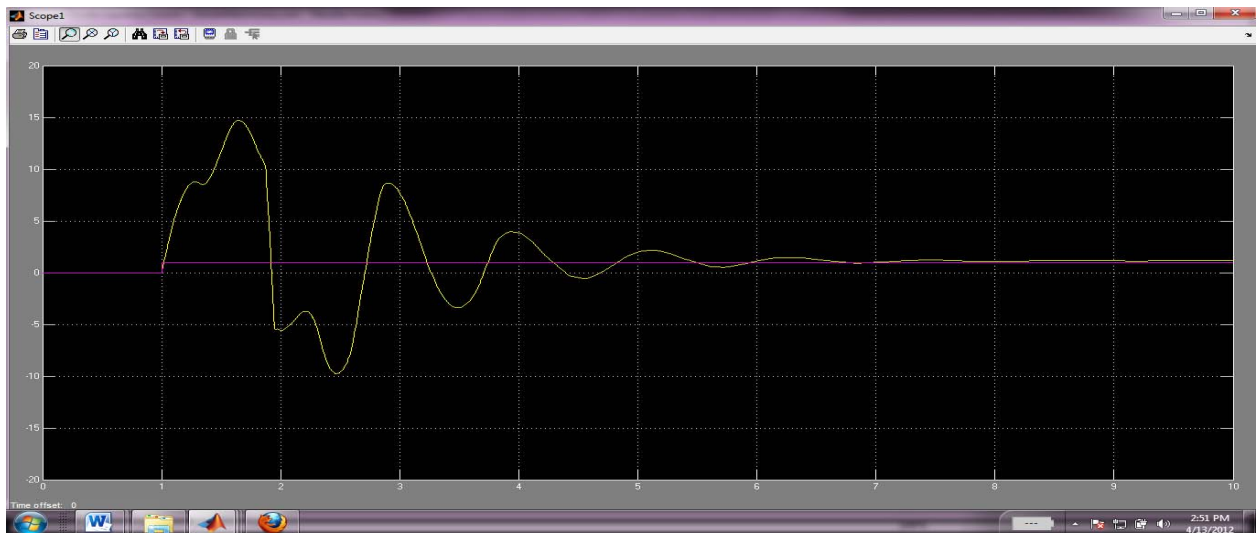


Fig. 15. The response of the system for yaw angle.

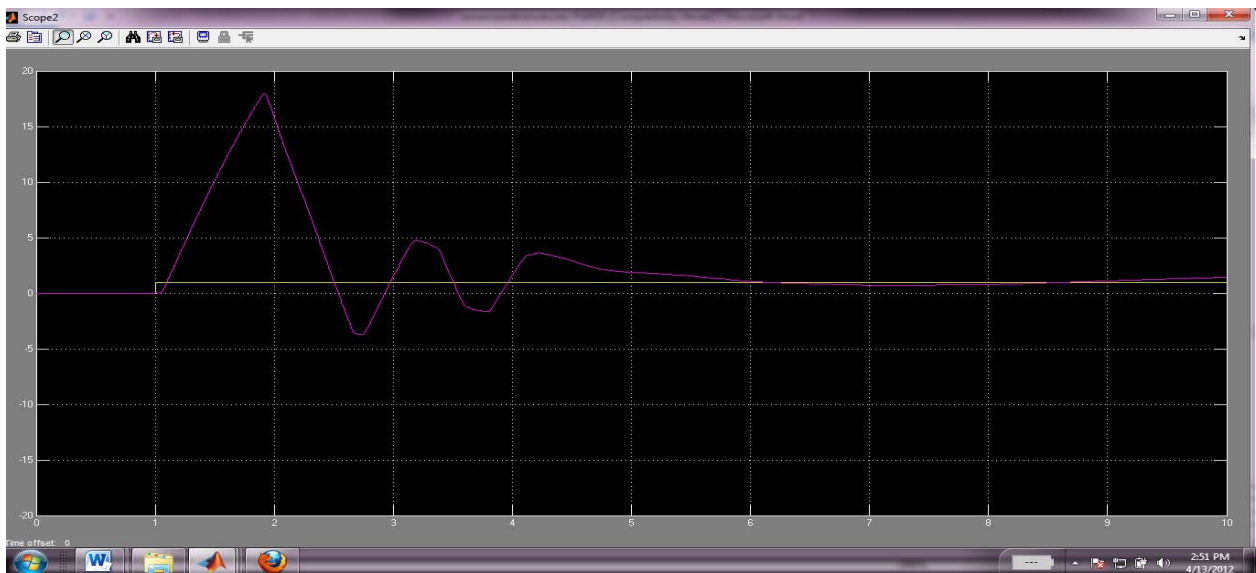


Fig. 16 Step response for roll angle.

5. Conclusion

In this paper, the model of an aircraft lateral control system that is helpful in developing the control strategy for an actual aircraft system was designed for Matlab/Simulink environment and control methods were proposed for this system. The effect of roll control surface on yaw and vice versa is also taken into consideration. The system will consider the cross coupling between the transfer functions so it will be more efficient and accurate than separate controller designs Using a fuzzy controller will result in an excellent overall response of the system. .It can be seen from the results that the Fuzzy controller is not only controlling the nonlinear system, but also giving the desired efficiency.Future work will be mainly on designing a single fuzzy controller that will control both the yaw and roll simultaneously.Practically obtained results show that FLC controller relatively gives the best performance and using such controller increases speed of the time response.

Acknowledgment

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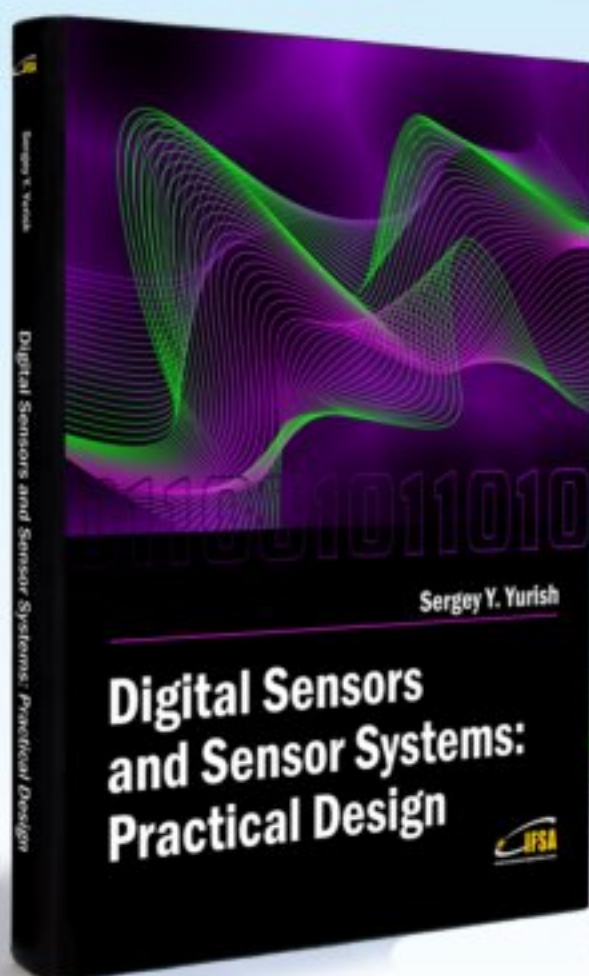
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