Designing a Fuzzy Logic Controller to Enhance Directional Stability of Vehicles under Difficult Maneuvers

Mehrdad N. Khajavi , Golamhassan Paygane, Ali Hakima

Abstract—Vehicle which are turning or maneuvering at high speeds are susceptible to sliding and subsequently deviate from desired path. In this paper the dynamics governing the Yaw/Roll behavior of a vehicle has been simulated. Two different simulations have been used one for the real vehicle, for which a fuzzy controller is designed to increase its directional stability property. The other simulation is for a hypothetical vehicle with much higher tire cornering stiffness which is capable of developing the required lateral forces at the tire-ground patch contact to attain the desired lateral acceleration for the vehicle to follow the desired path without slippage. This simulation model is our reference model.

The logic for keeping the vehicle on the desired track in the cornering or maneuvering state is to have some braking forces on the inner or outer tires based on the direction of vehicle deviation from the desired path. The inputs to our vehicle simulation model is steer angle δ and vehicle velocity V , and the outputs can be any kinematical parameters like yaw rate, yaw acceleration, side slip angle, rate of side slip angle and so on. The proposed fuzzy controller is a feed forward controller. This controller has two inputs which are steer angle δ and vehicle velocity V, and the output of the controller is the correcting moment M, which guides the vehicle back to the desired track. To develop the membership functions for the controller inputs and output and the fuzzy rules, the vehicle simulation has been run for 1000 times and the correcting moment have been determined by trial and error. Results of the vehicle simulation with fuzzy controller are very promising and show the vehicle performance is enhanced greatly over the vehicle without the controller. In fact the vehicle performance with the controller is very near the performance of the reference ideal model.

Keywords—Vehicle, Directional Stability, Fuzzy Logic Controller, ANFIS..

I. INTRODUCTION

VEHICLE which are turning or maneuvering at high speeds are susceptible to sliding and subsequently deviate from desired path. The reason of this phenomenon is the insufficiency of lateral forces developed at tire-ground patch contact to attain the desired lateral acceleration. This path deviation is very dangerous and can cause human injuries and fatalities as well as financial losses.

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Nowadays we are witnessing an intense competition in automobile industry to improve comfort and safety of newly designed and manufactured automobiles. Using more sensors and control systems are an integral part of new automobiles. Safety related vehicle control subsystems such as drive dynamics control, anti-lock brake system are among the most important one. Yaw dynamics control is a field that has attracted the interest of many researchers. The main objective in this field is to enable the driver to pursue his or her desired path regardless of the driving conditions such as high velocity and difficult maneuvers. Tahami and his colleagues have designed a fuzzy logic direct yaw moment control for all wheel electrical vehicles [1]. Boada et al have designed a fuzzy controller to control yaw rate and side slip angle simultaneously [2].

In this research a 4 DOF vehicle model have been considered as the system to be controlled. Two different simulations have been done. One is for the original vehicle for which a fuzzy controller is going to be designed. The other one is the reference vehicle whose behavior is going to be imitated by original vehicle. The two simulations are alike except for the cornering tire coefficient of the reference vehicle which is considered four times of the actual value to develop enough friction force at tire-ground patch contact to avoid sliding of the vehicle on turning at high velocities.

Due to the lack of experimental facilities and high costs of such facilities, simulation software namely MATLAB/SIMULINK/SIMMECHANICS have been used for inferring the dynamic behavior of the vehicle and designing controller. In section II the governing equations of the vehicle roll/yaw behavior is derived.

II. MATHEMATICAL MODELLING

The first and most important phase of any simulation is deriving the equation governing the system or process under study. Of course describing a real process or system as it is in terms of equations requires a lot of simplifying assumptions, without them it is very difficult if not impossible to explain the behavior of real process or system. So there must be a compromise between the accuracy and complexity of the model. In the case of the modeling of the mechanical systems either Newton second law or Lagrange equations are the basic equations. In this paper we have used the model of the vehicle which have been developed by S. Takanoa & M. Nagai [3]. Figures 1,2 show the physical model of the vehicle from front and top view
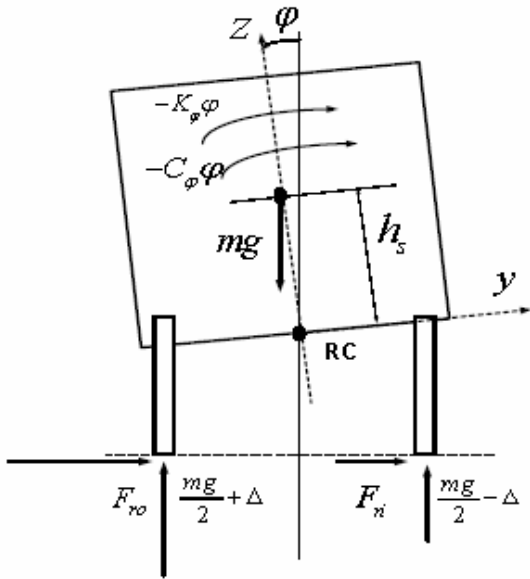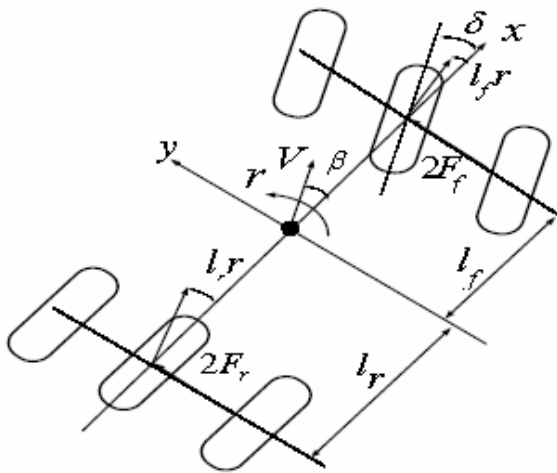
Fig, 1. Front view of the vehicle

Fig. 2. Top view of the vehicle

Using Newton second law, the governing equations of yaw/roll motion of the vehicle are as follows:

Lateral acceleration:

$$mV(\overset{\cdot}{\beta}+r)-m_sh_s\overset{\cdot\cdot}{\phi}=2F_f+2F_r \tag{1}$$

Yaw motion:

$$I\overset{\cdot}{r}-I_{XZ}\overset{\cdot\cdot}{\phi}=2l_fF_f+2l_rF_r \tag{2}$$

Roll motion:

$$I_\phi\overset{\cdot\cdot}{\phi}-m_sh_sV(\overset{\cdot}{\beta}+r)-I_{XZ}\overset{\cdot}{r}=\sum M_X \tag{3}$$

Longitudinal acceleration:

$$\sum F_X = ma \tag{4}$$

Combining the above equations, the following equations for rate of change of side slip angle $\overset{\cdot}{\beta}$, yaw acceleration $\overset{\cdot}{r}$, and roll acceleration $\overset{\cdot\cdot}{\phi}$ results:

$$\overset{\cdot}{\beta}=\frac{1}{mV}\left\{2k_f\delta-2(k_f+f_r)+r\left[-mv-\frac{2(l_fk_f-l_rk_r)}{V}\right]\right.$$
$$\left.+m_sh_s\overset{\cdot\cdot}{\phi}+2\left[\frac{\partial\alpha_f}{\partial\phi}k_r+\frac{\partial\alpha_r}{\partial\phi}k_f\right]\right\}$$

$$\overset{\cdot}{r}=\frac{1}{I}\left\{2l_fk_f\delta+\beta\left[-2(l_fk_f-l_rk_r)+r\left(-\frac{2(l_f^2k_f+l_r^2k_r)}{V}\right)\right]\right\}$$
$$+I_{XZ}\overset{\cdot\cdot}{\phi}+2\phi\left[\frac{\partial\alpha_f}{\partial\phi}k_fl_f-\frac{\partial\alpha_r}{\partial\phi}k_rl_r\right]+FLCYM$$

$$\overset{\cdot\cdot}{\phi}=\frac{1}{I_\phi}\left\{I_{XZ}+m_sh_sV(r+\overset{\cdot}{\beta})+\phi(-k_\phi+m_sh_sg)-\overset{\cdot}{\phi}C_\phi\right\} \tag{5}$$

To simulate the above equations, SIMULINK/SIMMECHANICS from MATLAB has been used [4]. In the above equations the term FLCYM stands for Fuzzy Logic Yaw Moment which is generated by the controller to redirect the vehicle to desired path.

The Simulink/Simmechanic inputs which simulates the actual vehicle and reference vehicle are steer angle δ and vehicle velocity V. The spec of the vehicle for which the controller was designed is given in table 1 which belongs to Samand a brand from IRANKHODRO Company.

TABLE 1 VEHICLE PARAMETERS

Definition	Symbol	Unit	Value
Vehicle Mass	m	kg	1300
Yaw moment of inertia	I	Kg.m2	1627
Roll moment of inertia	If	Kg.m2	500
Roll moment arm	hs	m	0.5

Distance from front axle to c.g	lf	m	1
Distance from rear axle to c.g	lr	m	1.45
Front tire cornering stiffness (actual)	Kf	N/rad	35000
Rear tire cornering stiffness (actual)	Kr	N/rad	35000
Sprung mass	Ms	Kg	1167
Roll stiffness	$K\varphi$	N.m/rad	66175
Roll damping coefficent	$C\varphi$	N.m.s/rad	3511
Gravitational acceleration	G	m/s2	9.81
Change of slip angle the front wheel due to a unit roll angle	$\dfrac{\partial \alpha_f}{\partial \phi}$		-0.2
Change of slip angle of the rear wheel due to a unit roll angle	$\dfrac{\partial \alpha_r}{\partial \phi}$		-0.2

III. FUZZY LOGIC CONTROLLER DESIGN

The complexity and nonlinearity of the system equations justifies the use of Fuzzy Logic Controller for controller design strategy.

The FLC inputs are the difference between reference side slip angle and the actual side slip angle $\Delta\beta$ and the difference between reference yaw rate and actual yaw rate Δr. Figure 3 shows the structure of the FLC.
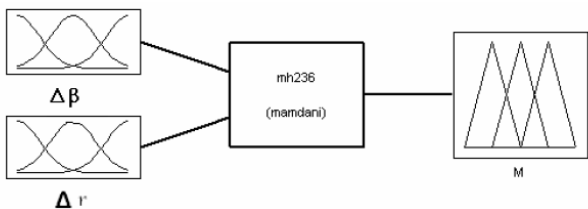

Fig, 3. FLC Structure

Mamdani fuzzy inference system is used in this research. The input variables and output variable must have specific membership functions which are assigned to them by an expert who is familiar with the behavior of the system. In this research because the actual vehicle and the testing facilities and instruments were not available the simulation which is based on the governing equations of the system were used to get the insight to the actual vehicle behavior. After simulating the system for more than 1000 times the following membership functions are proposed for the inputs and outputs. Figure 4 shows the membership function for input $\Delta\beta$
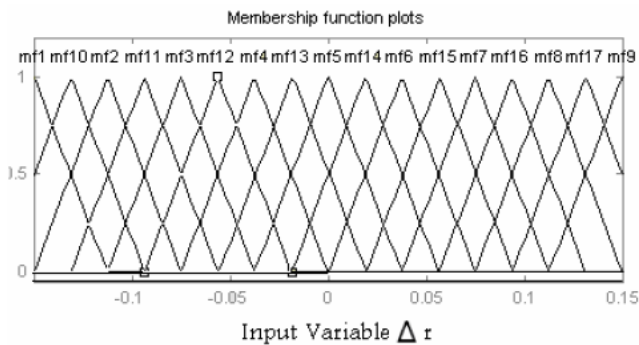
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Fig, 4. Membership function of input variable $\Delta\beta$

As can be seen in figure 4 there are 17 membership functions for input variable β Δ ten of which are triangular and the remaining seven are Gaussian. The range of this input variable is from -1 to +1.This choice is made after many trial and errors and trying to get the best results.

The membership function for the next input V is shown in figure 5. The range of this input variable is from -0.15 to +0.15. As can be seen in figure 5 seventeen membership functions all of them triangular have been assigned to this input variable.

Fig, 5. Membership function of input variable Δr

The output membership function for the correcting yaw moment is shown in figure 6. There are seventeen triangular membership functions for the output variable.

After assigning the membership functions, the fuzzy rules should be expressed. These rules are derived from the vehicle response without controller and then determining the appropriate control input to force the system to behave as desired by trial and error.
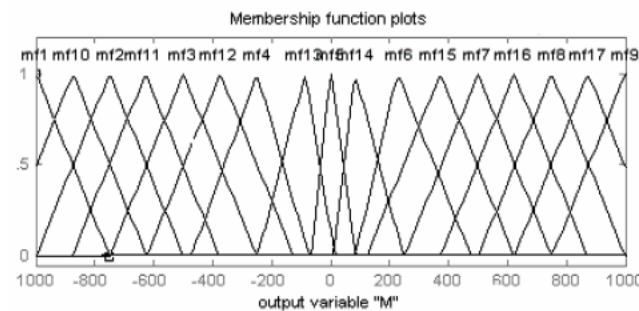

Fig. 6. Membership functions of output variable M

For example one of the fuzzy rules is expressed and explained as follows:

IF (beta is mf 1) then (m is mf 1)

This rule says that if the skidding velocity of the actual vehicle is much more than the reference vehicle then apply a positive and big moment to the vehicle.

The rest of the rules are also written in the same way.

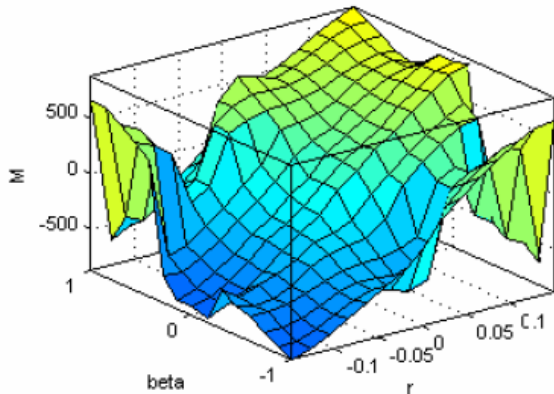The rule surfaces in a three dimensional graph is shown in figure 7.

Fig 7. Three dimensional graph of the rule surface

IV. SIMULATION RESULTS

The results of the vehicle response for different maneuvers are shown bellow:

1) Maneuver A: Vehicle velocity 160 km/h and 5 degree step steer angle.

The simulation results for this case are shown in figures 8 to 11.
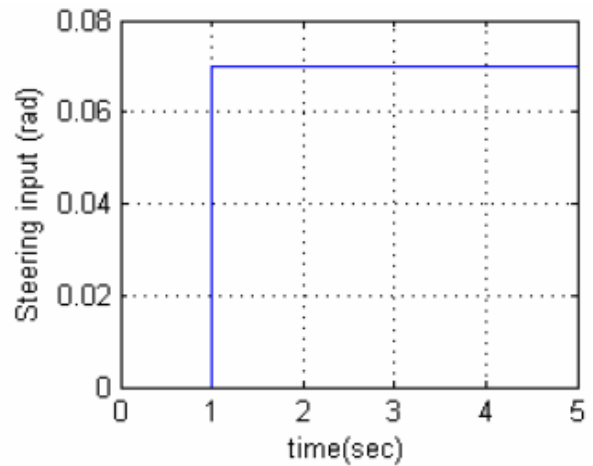
Fig, 8. Step steer input
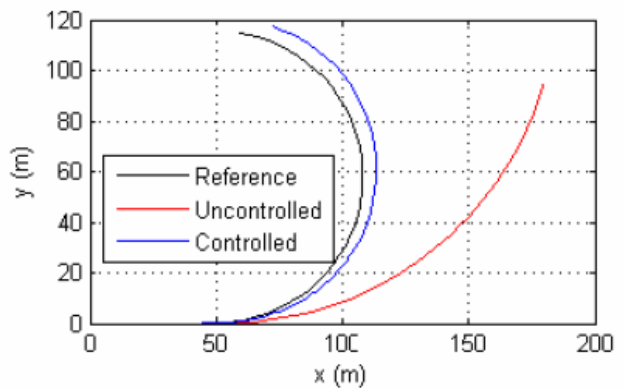
Fig, 9. Vehicle position
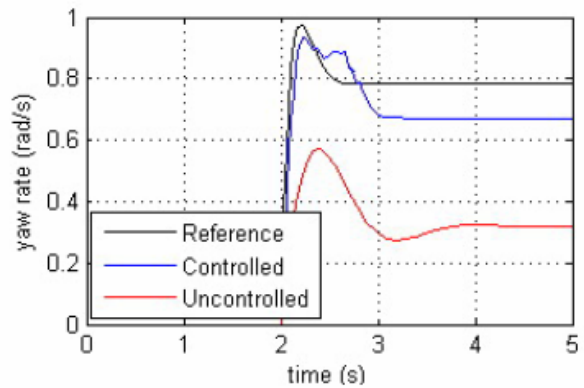
Fig, 10. Yaw rate
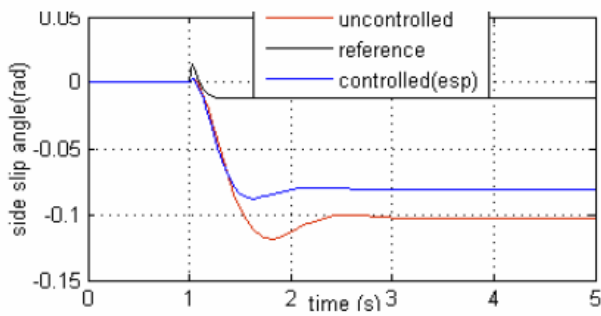
Fig, 11. Side slip angle

II) Maneuver B: Vehicle velocity 130 km/h and double steer input.

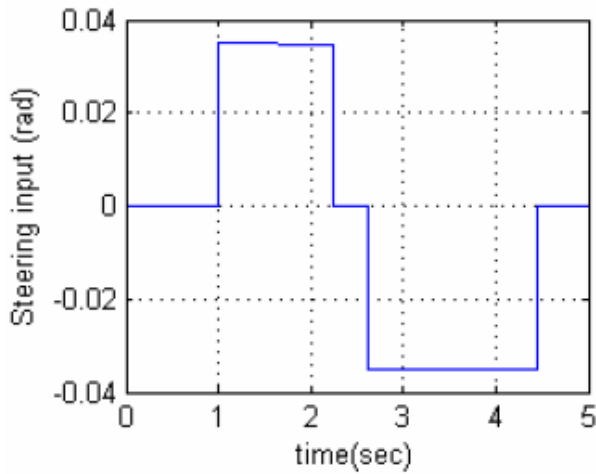Figures 12 to 15 show the results for this case.
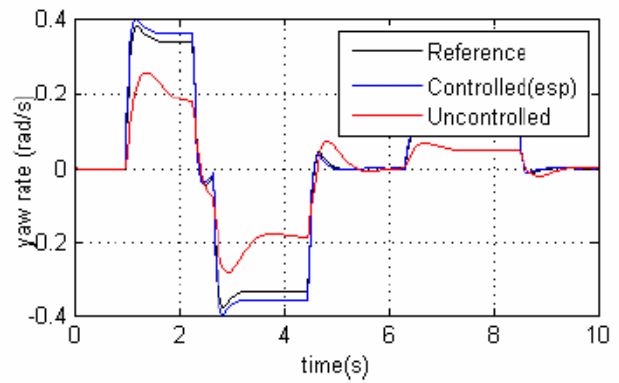

Fig, 12. Double step steer input

Fig, 13. Vehicle position

Fig, 14. Yaw rate

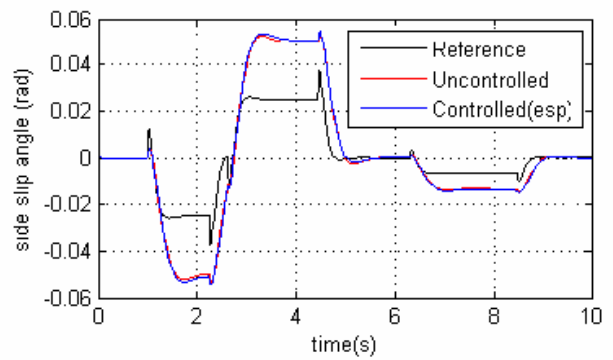
Fig, 15. Side slip angle

III)   Maneuver C: Vehicle velocity 80 km/h and 20 degree step steer input.
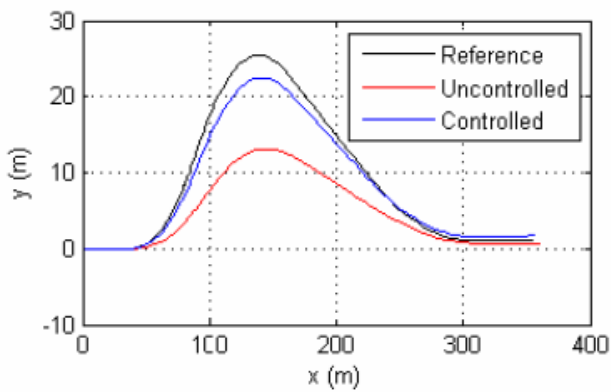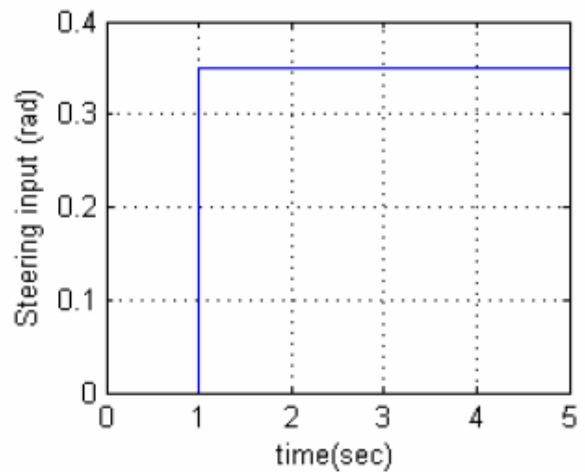
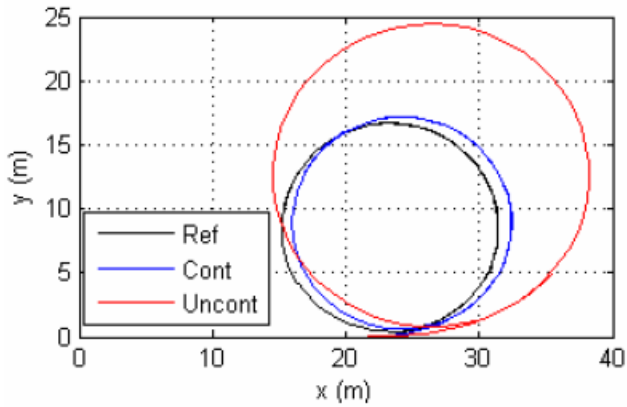Figures 16 to 18 show the results.

Fig, 16. 20 degree step steer input
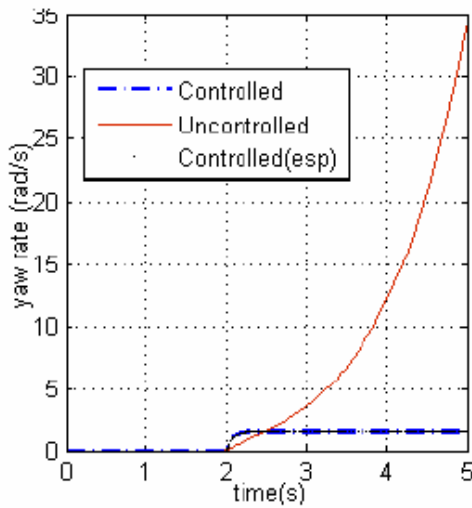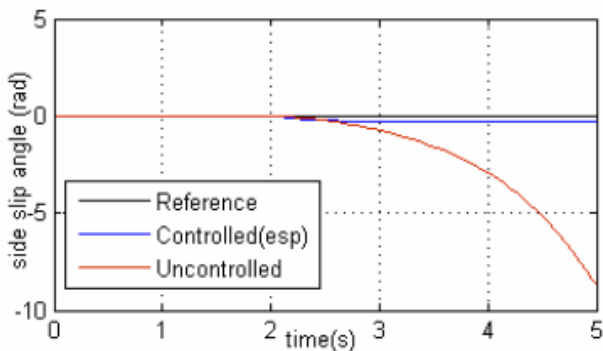
Fig, 17. Vehicle position

The results show good performance of the controller in regards to controlling position of the vehicle as well yaw rate, but the side slip angle is not controlled as good as the two latter variables. Another interesting issue in the proposed controller is its robustness due to mass and geometrical changes of the vehicle characteristics. Different simulation with the entirely different mass and geometrical characteristics for the vehicle shows good performance of the proposed FLC. This robustness characteristic of the controller which is an inherent feature of FLC makes the proposed controller, ideal for practical implementations.

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[4] MATLAB Software, Version 7.4, Fuzzy Logic Toolbox, 2008.

Fig, 18. Yaw rate

Fig, 19. Side slip angle