Fuzzy Controller Design for a Novel Vehicle Rollover Prevention system

Pedram Safi and Moein Mahmoodzadeh Entezari

***Abstract*—Vehicles rollover is considered as one of the most significant causes of injuries and fatalities in road accidents. Thus, automotive engineers have always been interested in devising mechanisms or modifying the vehicle design in order to prevent rollover. In this research, an active stabilizer is used to improve the roll stability of a SUV (sport utility vehicle). A novel fuzzy mamdani controller is designed in order to improve the performance of the anti-rollover system. Performance of the system is then evaluated using CarSim which is a car dynamic simulation software, while the Controller is implemented in Simulink Environment. Matlab/CarSim Co-simulation of the models during standard maneuvers demonstrates the versatility and reliability of the proposed mechanism in improving the vehicle roll motion stability and thus preventing rollover when necessary.**

***Index Terms*—Rollover prevention, fuzzy controller, CarSim.**

I. Introduction

Rollover is the second most dangerous car crash on American Highways. 9,882 people were killed in light vehicle rollover crashes, including 8,146 killed in single-vehicle rollovers, in the year 2000. Vehicles with high centers of gravity (CG), e.g., Sport Utility Vehicles (SUVs) are becoming more and more popular. These vehicles are more likely to rollover during extreme maneuvers compared to ordinary cars. [1]

In this paper enhancing vehicle roll stability is considered using an active stabilizer implemented on the vehicle roof. Vehicle longitudinal speed then results in generating a pair of force on both sides of the vehicle using airfoil-shaped spoilers, in order to generate enough torque in proper directions, which is able to reduce vehicle roll angle and improve stability during different maneuvers. A Fuzzy Logic Controller (FLC) is developed based on mamdani method and is utilized in controlling the spoiler system. A CarSim SUV Class D model is used within Simulink Environment in order to evaluate the system performance during double lane change and fishhook maneuvers. CarSim is a parameter based vehicle dynamics modeling software from Mechanical Dynamics Corporation (MSC).It provides different precompiled vehicle models which can be easily included in the Simulink models. In this paper, a full vehicle dynamic model for simulation is developed within CarSim.[7]The Co-simulation of Simulink and CarSim verifies the correct performance of the proposed mechanism and the applied control method during maneuvers at different vehicle speeds. Simulations show that the suggested system reduces roll angle considerably and also is capable of preventing vehicle rollover when necessary. Second chapter of this paper includes vehicle models and equations. In Chapter III, the proposed anti-rollover mechanism is explained. The control strategy and controller design are discussed in chapter IV and chapter V presents simulation results. Finally chapter VI includes Conclusions.

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The authors are with the Department of Mechanical Engineering, Islamic Azad University – Karaj branch, Karaj, Iran (e-mail: Safi.pedram@gmail.com; m.m.entezari@gmail.com)

II. Vehicle Models

Most modern control design methodologies are model-based. The first step in the design process therefore consists of obtaining a suitable model. In many cases several models are required for different purposes, such as design, reference generation, and simulation. Vehicle modeling is divided into two areas: tire modeling and chassis modeling. Tire modeling deals with understanding the forces that arise at the tire-road contact point. Chassis modeling involves determining the behavior of the vehicle when subject to these external forces. [2]

A. Tire Models

All road vehicles interact with the road surface via tires. More specifically, the tires are responsible for generating those forces which are required to alter the vehicle's speed and course according to the driver's inputs. Tires functions are complicated, and modeling is therefore difficult. A simple linear approximation of Magic Formula can be used. [3]

$$F_y = C_{F\alpha}\alpha + C_{F\gamma}\gamma \quad (1)$$

$C_{F\alpha}$ is the lateral slip stiffness, α is slip angle, $C_{F\gamma}$ is camber stiffness, γ is camber angle.

B. Vehicle Model

In order to incorporate the effects of the individual tire forces, as well as suspension and a more accurate representation of the roll dynamics, a two-track model can be used, shown in Fig. 1 [6].The suspension is modeled as atorsional spring and damper system. Therefore, the Nonlinear 4 DOF model of the vehicle can be obtained as following using Euler-Lagrange method. [2]

$$m[\dot{u} - \dot{\psi}v - h(2\dot{\phi}\dot{\psi} + \phi\ddot{\psi})] = F_{xT} \quad (2)$$

$$m[\dot{v} + \dot{\psi}u + h(\ddot{\phi} - \dot{\psi}\phi)] = F_{yT} \quad (3)$$

$$I_{zz}\dot{r} - mh(\dot{u} - \dot{\psi}v)\phi + (I_{zz}\theta_r - I_{xz})\ddot{\phi} = M_T \quad (4)$$

$$(I_{xx}+mh^2)\ddot{\phi}+mh(\dot{v}+\dot{\psi}u)+(I_{zz}\theta_r-I_{xz})\ddot{\psi}-(I_{yy}+mh^2-I_{zz})\dot{\psi}^2\phi+(C_\phi-mgh)\phi-K_\phi\dot{\phi}= \quad (5)$$

$$\begin{bmatrix} m & 0 & -mh\phi & 0 & 0 \\ 0 & m & 0 & mh & 0 \\ -mh\phi & 0 & I_{zz} & I_{zz}\theta_r-I_{xz} & 0 \\ 0 & mh & I_{zz}\theta_r-I_{xz} & I_{xx}+mh^2 & K_\phi \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix}\dot{v}_x \\ \dot{v}_y \\ \ddot{\psi} \\ \ddot{\phi} \\ \dot{\phi}\end{bmatrix}= \begin{bmatrix} F_{xT}+m\dot{\psi}v+2mh\dot{\phi}\psi \\ F_{yT}-m\dot{\psi}u+mh\dot{\psi}^2\phi \\ M_T-mhv\dot{\psi}\phi \\ -mhu\dot{\psi}+(mh^2+I_{yy}-I_{zz})\dot{\psi}^2\phi-(C_\phi-mgh)\phi \\ \dot{\phi} \end{bmatrix} \quad (6)$$

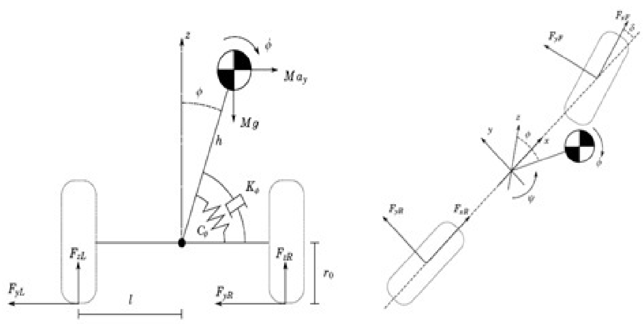

Fig. 1. Vehicle Model

III. ROLLOVER PREVENTION MECHANISM AND MODELS

Instead of using mathematical model of the vehicle, CarSim software can be utilized in order to analyze the vehicle response subjected to different inputs. The initial conditions such as steering angle and vehicle speed and other parameters of the vehicle such as mass, dimensions and aerodynamic characteristics can be easily specified in CarSim environment. After preparing the model, a S-function is generated which can be sent directly to Simulink environment in order to perform the simulation. In this research, the control system and active stabilizer system are both modeled in Simulink environment. Fig. 2 illustrates the final model structure in Simulink. The spoiler subsystem consists of the aerodynamic model and is designed to output the generated lift by airfoils when longitudinal velocity of the vehicle and the airfoils angle are known. The vehicle velocity signal can be obtained from CarSim Subsystem and the spoiler angle of attack is specified by fuzzy controller output which is considered as the control signal. The aerodynamic model is presented in Fig. 3.In this work, roll behavior of the vehicle has been improved by means of an intelligent stabilizer which is able to produce lift force in upwards and downwards directions by means of its airfoils. This mechanism can be implemented on the vehicle roof and is also able to transmit the aerodynamic force from the airfoil surface to the vehicle roof and body. Thus, an appropriate torque will be applied to the vehicle in order to prohibit the roll angle to exceed from the threshold which results in vehicle unstable conditions and then rollover. The airfoil should be of symmetrical type due to the fact that the amount of generated lift force should be the same with positive and negative airfoil angles of attack. Thus an equal amount of force will be applied on both sides of the vehicle when roll angle is not zero. On the other hand, the spoiler system should not generate lift force when the vehicle roll angle is zero. Symmetrical airfoils do not generate lift with zero angle of attack. In this research, we have utilized a NACA0035 standard airfoil.

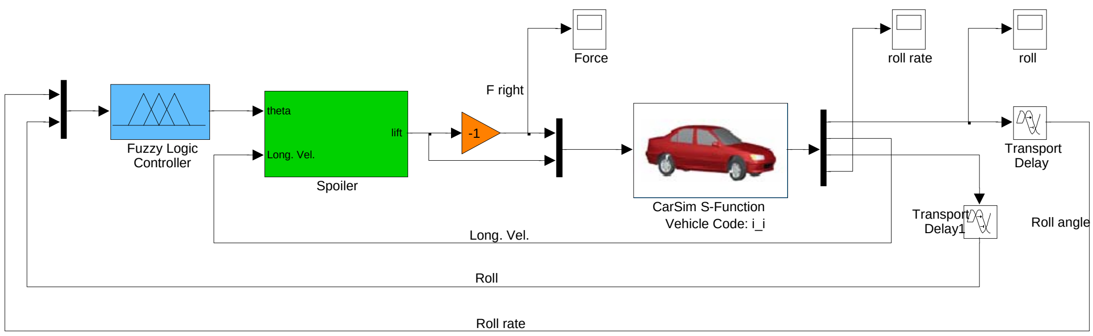

Fig. 2. Final model

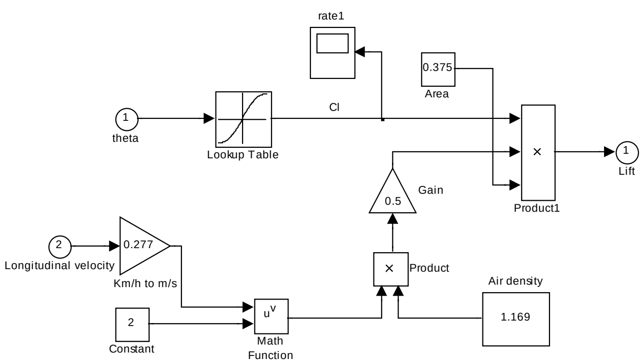

Fig. 3. Aerodynamic subsystem

Javafoil [4] software is also used in order to analyze the airfoil with different angles of attack and obtain the amount of lift coefficient in each position. Fig. 4 presents the data obtained from JavaFoil. This set of data then can be used in simulation by means of a look-up table, which converts the table input which is airfoil angle to correspondent lift Coefficient (C_L).

IV. FUZZY STABILITY CONTROLLER

The structure of integrated vehicle model and fuzzy stability controller is illustrated in Fig. 5 [5].The stability controller inputs are roll angle and roll angle change rate. The control signal is airfoil angle (θ) which is the spoilersubsystem input. The spoiler subsystem then calculates the generated lift forces F_1 and F_2 by means of desired airfoil angle along with vehicle longitudinal velocity. A pair of equal forces with opposite directions is then applied to the sides of the vehicle body in order to reduce the vehicle tendency for rollover. A mamdani inference engine is used in the proposed fuzzy controller. Input and output membership functions are depicted in Fig. 6 & 7. Table I also includes fuzzy logic rules. Fig. 8 illustrates fuzzy rules surface presentation.

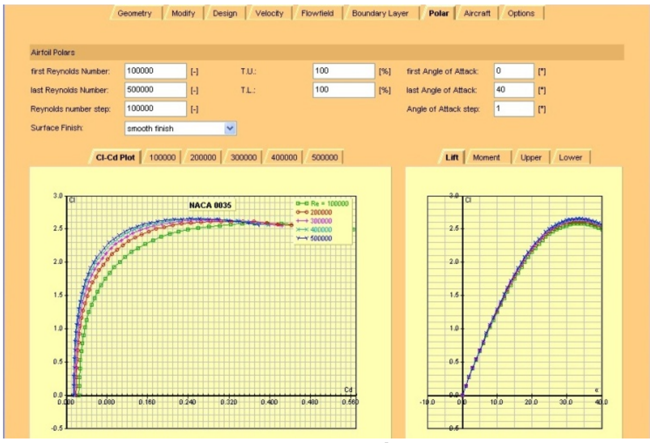

Fig. 4. JavaFoil

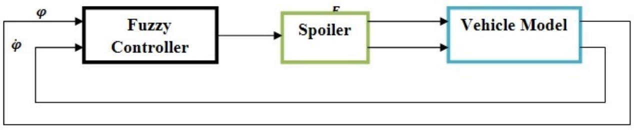

Fig. 5. Model structure

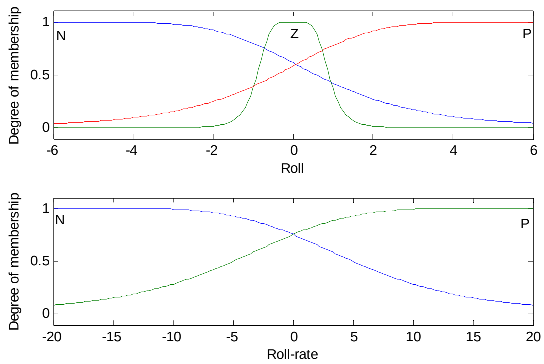

Fig. 6. Input membership functions

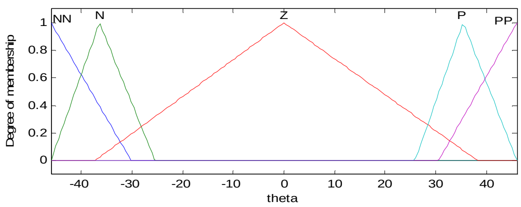

Fig. 7. Output membership functions

TABLE I: Fuzzy Rules

Roll ---- Roll Rate	Positive	Negative
Positive	Too small	small
Neutral	small	large
Negative	large	Too large

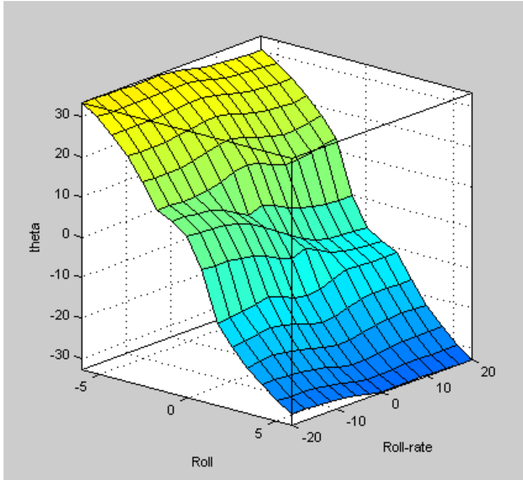

Fig. 8. Fuzzy rules surface

V. Simulation and Results

In order to verify the performance of the vehicle stability controller, two different maneuvers were selected which are Double lane change and fishhook maneuvers. The simulation results are reported in this section.

A. *Double-Lane Change*

The vehicle is driven on a double lane change with the velocity of 150 km/h which is a CarSim standard test. As shown in Fig. 9, the system can reduce the vehicle roll angle in sudden lane changes and thus improve the stability and reduce the risk of rollover. In Fig. 10 Roll angle change rate is compared for two types of vehicles.

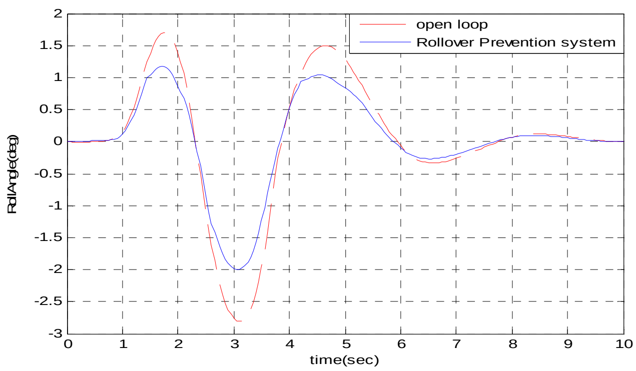

Fig. 9. Roll angle comparison - double lane change maneuver

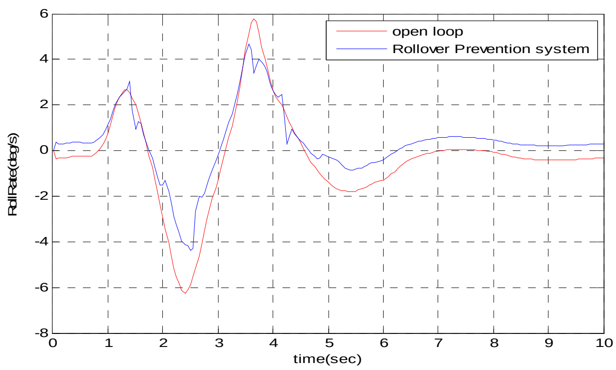

Fig. 10. Roll rate comparison - double lane change maneuver

As depicted in this figure roll angle change rate can also be decreased by the proposed system and thus vehicle tendency for rollover can be controlled.

B. Fishhook

The vehicle is also driven on a Fishhook maneuver with velocity of 100 Km/h. the roll angle and its change rate are also illustrated in Fig. 11& 12. As shown, the proposed rollover prevention mechanism and designed fuzzy controller can reduce roll angle and its change rate during this maneuver and thus improve the roll behavior of the vehicle.

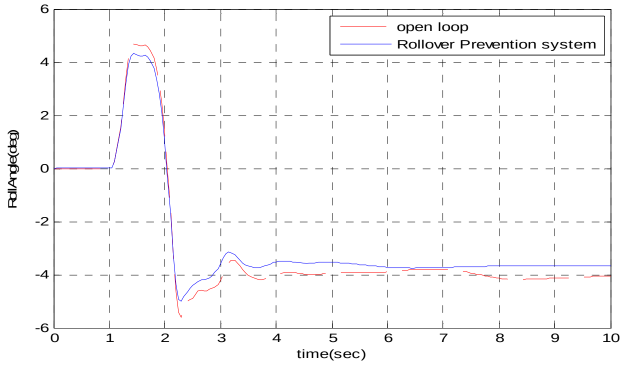

Fig. 11. Roll angle comparison in fishhook maneuver

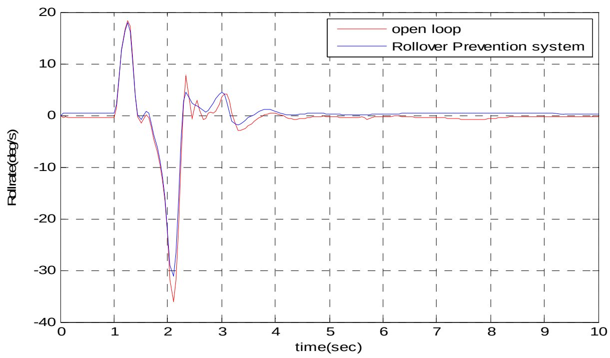

Fig. 12. Roll rate comparison in fishhook maneuver

C. Rollover Prevention

We have also examined the system reliability in emergency conditions. In this test we used a SUV with higher Center of gravity compared to the one used in previous tests. Rollover is more likely to happen in vehicles with a higher CG. The vehicle is driven on a fishhook with velocity of 120 Km/h. as illustrated in Fig. 13 Rollover happens approximately 3 seconds after the test starts. It is also shown that utilizing the proposed rollover prevention system effectively improves the roll behavior of the vehicle and prevents rollover.

VI. Conclusions

In this paper, a fuzzy controller was designed for an anti-rollover system implemented on a CarSim Class D SUV. Simulink was also used in order to implement the fuzzy controller and also the active stabilizer subsystem. Other parameters of the vehicle were defined via CarSim. Tests were done with different maneuvers and results show versatility and reliability of the proposed mechanism and the fuzzy stability controller. It was shown that the proposed integrated controller and active stabilizer system are able to reduce the lateral acceleration and roll angle and thus improve the vehicle roll motion and prevent rollover when necessary.

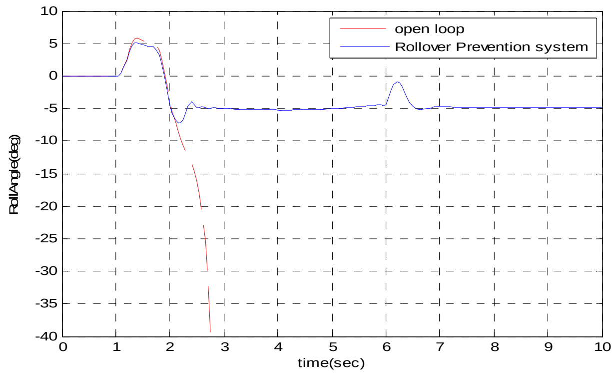

Fig. 13. Rollover prevention

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