

## Full car Model Active Suspension System with PID and Fuzzy Controls to Improve Ride Comfort

Salem M.M.M.

Automotive and tractor Dept, Faculty of Eng., Minia University, Minia, Egypt  
[zeyadslm@gmail.com](mailto:zeyadslm@gmail.com), [ali\\_tawwab@hotmail.com](mailto:ali_tawwab@hotmail.com)

**Abstract:** The purpose of any suspension system is to improve ride comfort and handling. This is achieved by controlling the state variables in order to reduce the effect of road input vibration (discomfort). This paper presents the modeling and validation of a 7-degree of freedom (DOF) full vehicle model to study ride performance of vehicle. To improve suspension control system that can reduce roll over effect and improve ride comfort, dynamic modeling of passive vehicle model was constructed. Such simulation model was developed in MATLAB Simulink software. Several assumptions related to 7-degree of freedom modeling were made and stated in this paper. This vehicle model was validated using vehicle dynamics simulation software. The validation was done by comparing the simulation results. In this paper introduced the concepts of PID and Fuzzy logic and its application toward the development of active suspension system. The fuzzy logic based model is being developed based on inputs, body acceleration, suspension working space and dynamic tyre distance. The control signal, which is a function of inputs, is determined from the rule base. The results show major improvement over passive suspension system and minor improvement over PID control.

[Salem M.M.M. **Full car Model Active Suspension System with PID and Fuzzy Controls to Improve Ride Comfort**. *J Am Sci* 2013;9(12):633-645]. (ISSN: 1545-1003). <http://www.jofamericanscience.org>. 82

**Keywords:** Vehicle dynamics, PID control, fuzzy logic control, Ride comfort, Active suspension system, and Full car model.

### 1. Introduction

Suspension system is classified into three categories: passive, active and semi-active suspension system. Therefore, the suspension controller should enhance suspension performance by controlling the related suspension parameters to improve ride quality and road handling [1,2]. A fuzzy logic is a new digital control methodology that combines multi valued logic, probability theory, artificial intelligence and neural networks. Fuzzy logic, unlike crisp logic, allows a partial membership. The basic method of designing suspension system is to use a sprung and a parallel damper laced between the vehicle body and each of the wheels [3]. During suspension system design, it is important to main good ride quality as well as good road handling especially during cornering which is difficult to maintain by passive suspension system. In semi active suspension, is used to replace the damper [4]. This model enables us to develop a controller capable providing the desired suspension response [5]. Fuzzy logic based control does not require a mathematical model since it is a rule based system [6]. Therefore, fuzzy logic control has an advantage over classical controller when it is applied to ill-define and complex systems. Many control methods have been proposed to overcome these suspension problems. Many active suspension control approaches such as Linear Quadratic Gaussian (LQG) control, adaptive control, and non-linear control are developed and proposed so as to manage the occurring problems [7,8]. During the last decades fuzzy logic

has implemented very fast hence the first paper in fuzzy set theory, which is now considered to be the influential paper of the subject, was written [9], who is considered the founding father of the field. Then developed and demonstrated the viability of Fuzzy Logic Control (FLC) for a small model steam engine [10]. Replacement of the spring-damper suspensions of automobiles by active systems has the potential of improving safety and comfort under nominal conditions. But perhaps more important, it allows continuous adaptation to different road surface quality and driving situations [11,12]. For the design of active suspension we know how to build a model and how to define the objective of the control in order to reach a compromise between contradictory requirements like ride comfort and road holding by changing the force between the wheel and chassis masses [13]. In the recent past, it has been reported on this problem successively, about the base of optimization techniques, adaptive control and even, H-infinity robust methods. In this study, semi-active suspension system for a quarter car is considered, PID and fuzzy logic controllers are designed when the vehicle is running on random road surface [14].

### Mathematical modeling

The full vehicle model in this study is based on a four wheels vehicle. The full vehicle model consists of 7-degree of freedom which involves vehicle body bounce, pitch, roll, and four wheels vertical motions. Fig. 1 shows the full vehicle model. The equations of motion are:

$$m_1 \ddot{z}_{WFL} = k_t(q_1 - z_{WFL}) + k_{SFL}(z_{SFL} - z_{WFL}) + c_1(\dot{z}_{SFL} - \dot{z}_{WFL}) \tag{1}$$

$$m_2 \ddot{z}_{WRL} = k_t(q_2 - z_{WRL}) + k_{SRL}(z_{SRL} - z_{WRL}) + c_2(\dot{z}_{SRL} - \dot{z}_{WRL}) \tag{2}$$

$$m_3 \ddot{z}_{WFR} = k_t(q_1 - z_{WFR}) + k_{SFR}(z_{SFR} - z_{WFR}) + c_3(\dot{z}_{SFR} - \dot{z}_{WFR}) \tag{3}$$

$$m_4 \ddot{z}_{WRR} = k_t(q_1 - z_{WRR}) + k_{SRR}(z_{SRR} - z_{WRR}) + c_4(\dot{z}_{SRR} - \dot{z}_{WRR}) \tag{4}$$

$$z_{SFL} = z - (a\theta + d\varphi) \tag{5}$$

$$z_{SRL} = z + (b\theta - d\varphi) \tag{6}$$

$$z_{SFR} = z + (a\theta - c\varphi) \tag{7}$$

$$z_{SRR} = z + (b\theta + c\varphi) \tag{8}$$

$$m\ddot{z} = k_{SFL}(z_{WFL} - z_{SFL}) + k_{SRL}(z_{WRL} - z_{SRL}) + k_{SFR}(z_{WFR} - z_{SFR}) + k_{SRR}(z_{WRR} - z_{SRR}) + c_1(\dot{z}_{WFL} - \dot{z}_{SFL}) + c_2(\dot{z}_{WRL} - \dot{z}_{SRL}) + c_3(\dot{z}_{WFR} - \dot{z}_{SFR}) + c_4(\dot{z}_{WRR} - \dot{z}_{SRR}) \tag{9}$$

$$J_x \ddot{\varphi} = -[k_{SFR}(z_{WFR} - z_{SFR}) + c_3(\dot{z}_{WFR} - \dot{z}_{SFR}) + k_{SRR}(z_{WRR} - z_{SRR}) + c_4(\dot{z}_{WRR} - \dot{z}_{SRR})]c + [k_{SFL}(z_{WFL} - z_{SFL}) + c_1(\dot{z}_{WFL} - \dot{z}_{SFL}) + k_{SRL}(z_{WRL} - z_{SRL}) + c_2(\dot{z}_{WRL} - \dot{z}_{SRL})]d \tag{10}$$

$$J_y \ddot{\theta} = -[k_{SFL}(z_{WFL} - z_{SFL}) + c_1(\dot{z}_{WFL} - \dot{z}_{SFL}) + k_{SRR}(z_{WRR} - z_{SRR}) + c_4(\dot{z}_{WRR} - \dot{z}_{SRR})]a + [k_{SRL}(z_{WRL} - z_{SRL}) + c_2(\dot{z}_{WRL} - \dot{z}_{SRL}) + k_{SFR}(z_{WFR} - z_{SFR}) + c_3(\dot{z}_{WFR} - \dot{z}_{SFR})]b \tag{11}$$

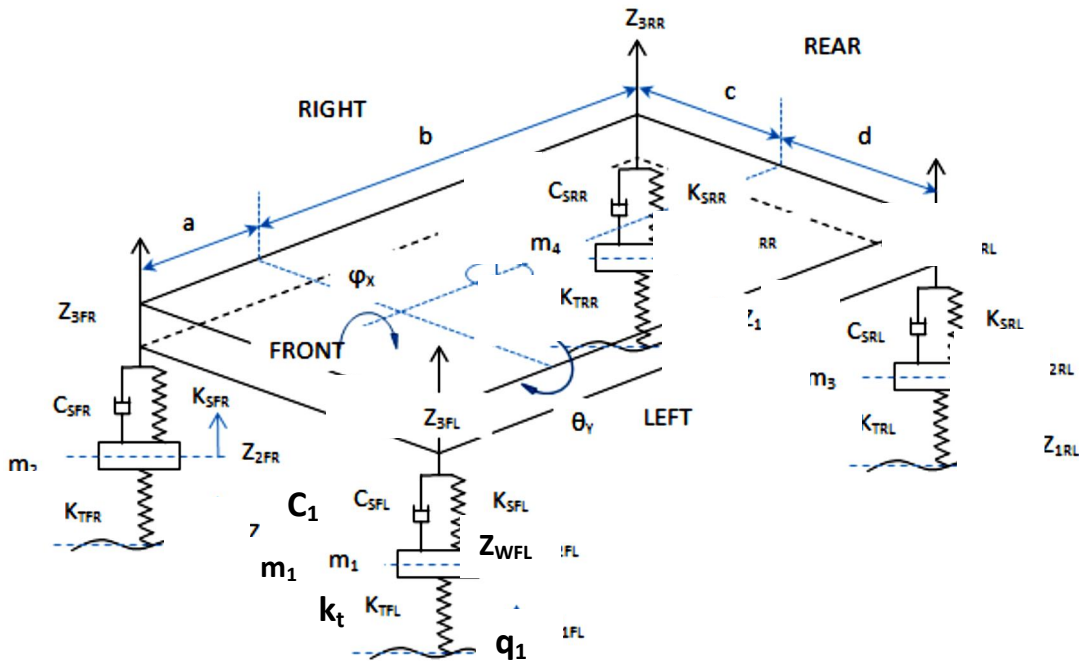


Fig. 1 Full Vehicle Model

**Proportional - Integral - Derivative (PID) controller**

PID stands for proportional, integral and derivative. These controllers are designed to eliminate the need for continuous operator attention. In order to avoid the small variation of the output at the steady state, the PID controller is so designed that it reduces the errors by the derivative nature of the controller. A PID controller is depicted in Figure 4. The set-point is where the measurement to be. Error is defined as the difference between set-point and measurement. (Error

= (set-point) – (measurement), the variable being adjusted is called the manipulated variable which usually is equal to the output of the controller. The controller output is proportional to the amount of time the error is present. Integral action eliminates offset. Controller Output = (1/Integral) (Integral of) e(t) d(t). With derivative action, the controller output is proportional to the rate of change of the measurement or error. The controller output is calculated by the rate of change of the measurement with time. Derivative action can compensate for a change in measurement.

Thus derivative takes action to inhibit more rapid changes of the measurement than proportional action. When a load or set-point change occurs, the derivative action causes the controller gain to move the “wrong” way when the measurement gets near the set-point. Derivative is often used to avoid overshoot. The difference between the actual acceleration and desired acceleration is taken as error in this study.

### Fuzzy Logic Methods

Fuzzy logic methods can be utilized in many ways in controlled suspension systems. With appropriate membership functions and rule bases it considered to be insensitive to model. Fuzzy logic is a method of controlling a system where all input conditions are not well defined. The implementation of fuzzy logic allows the use of rule based control whereby the controller is defined by abstract that give them a fuzzy quality. The linguistic control strategy of the fuzzy algorithm serves as a fuzzy process model. Because of the linguistic statements from the rule base of the fuzzy logic controller, the control strategy resembles human thinking process. Application of fuzzy logic method is presented. An appropriate input and output variable were decided. For example in active suspension system, using numerical simulation techniques, the optimum choice for state variables was the velocity and the acceleration of the sprung mass. The output of the controller was force and represented with  $u$  (force of the actuator). The universe of discourse for both the input and the output variables was divided into three sections using the following linguistic variables, P (positive), Z (zero), and N (negative). The universe of discourse for the input variable was found by subjecting the passive suspension to several different input conditions and viewing the maximum and minimum values for each particular input variable. Triangular membership functions were initially chosen but in triangular membership function there is a problem due to the inherent sharpness in the triangular membership function's shape. The controller will act very fast to the slightest change in velocity or acceleration. The trapezoidal membership function can produce smoother control action due to the flatness at the top of the trapezoid shape. Appendix (A) shows the full car model and Simulink.

### Results and Discussion

The full car suspensions for passive and active with PID and Fuzzy controls were simulated using MATLAB/SIMULINK [15]. Figs (a1, a2, a3, a4, a5 and a6) in appendix A show the simulation blocks diagrams. The theoretical results were made at three models passive, active suspension system fuzzy controller and active suspension system PID controller. The full car model parameters are shown in

the table 1. The simulation results of two types of controllers PID and fuzzy control and passive suspension systems are compared for step input road conditions as shown in Fig2. It can be seen the natural frequency of body mass for suspension systems are within the comfortable zone of 0.8-1.5 Hz, while passive suspension system the natural frequency is more compared to active suspension system since it uses more stiffer suspension at front and rear. Figs.(3&4) show the body acceleration, suspension working space and dynamic tyre load for passive, with different springs stiffness's in terms of time domain. It can be observed that the reduction of the body acceleration, suspension working space and dynamic tyre load peaks with decrease springs stiffness. Figs.(5&6) show the body acceleration, suspension working space and dynamic tyre load for passive, with different damping coefficients in terms of time domain. It can be observed that the reduction of the body acceleration, suspension working space and dynamic tyre load peaks with increase damping coefficient. Figs.(7&8) shows the body acceleration, suspension working space and dynamic tyre load for passive, with different tyre stiffness's in terms of time domain. It can be observed that the reduction of the body acceleration, suspension working space and dynamic tyre load peaks with decrease tyre stiffness. Figs.(9&10) show the body acceleration, suspension working space and dynamic tyre load for passive, with different delay times in terms of time domain. It can be observed that the reduction of the body acceleration, suspension working space and dynamic tyre load peaks with increase delay times stiffness. Figs.(11&12) show Comparison between the body acceleration, suspension working space and dynamic tyre load for active with PID and Fuzzy controls over the passive suspension system results. It can be clear that there is an improvement in ride comfort performance over passive. This indicates that the active with PID and fuzzy controls suspension systems are better than the passive.

**Table. 1 Full car suspension system components parameter.**

No	Parameters	Unit	Value
1	Sprung Mass	Kg	1140
2	Front& rear Unsprung Masses	Kg	60
3	Pitch Inertia	Kg m <sup>2</sup>	2460
4	Roll Inertia	Kg m <sup>2</sup>	460
5	Front & rear Suspension Stiffness	KN/m	15
6	Front & rear Damping	Ns/m	1500
7	Distance From C.G to Front Wheel	m	1.15
8	Distance From C.G to Rear Wheel	m	1.65
9	Front & rear Track Width	m	0.557
10	Front & rear Tyre Stiffness	KN/m	120

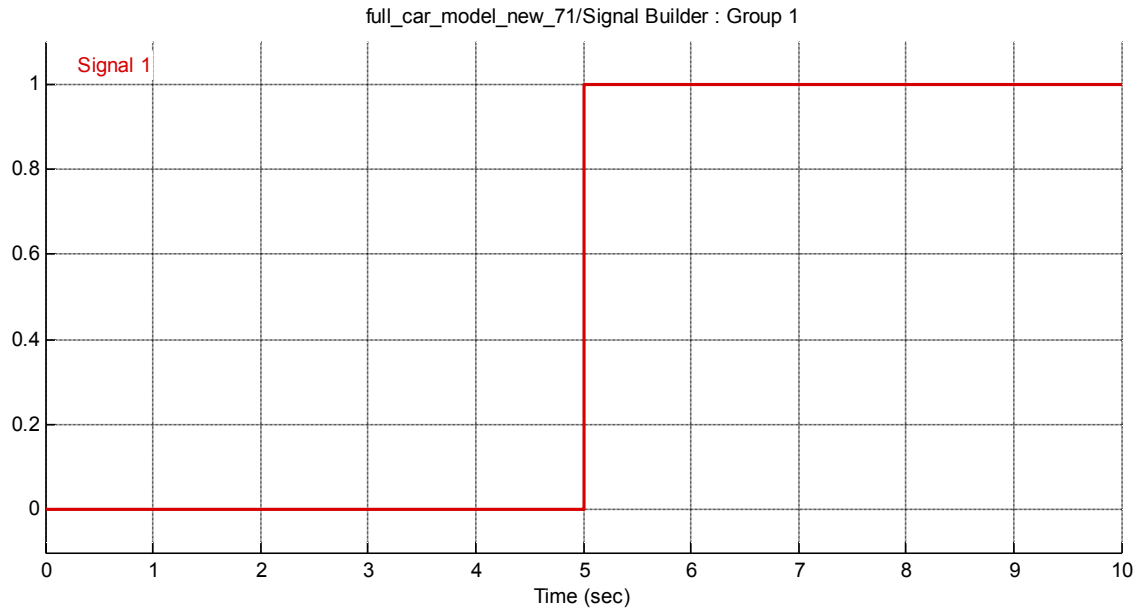


Fig. 2 step input excitation (road input/wheel)

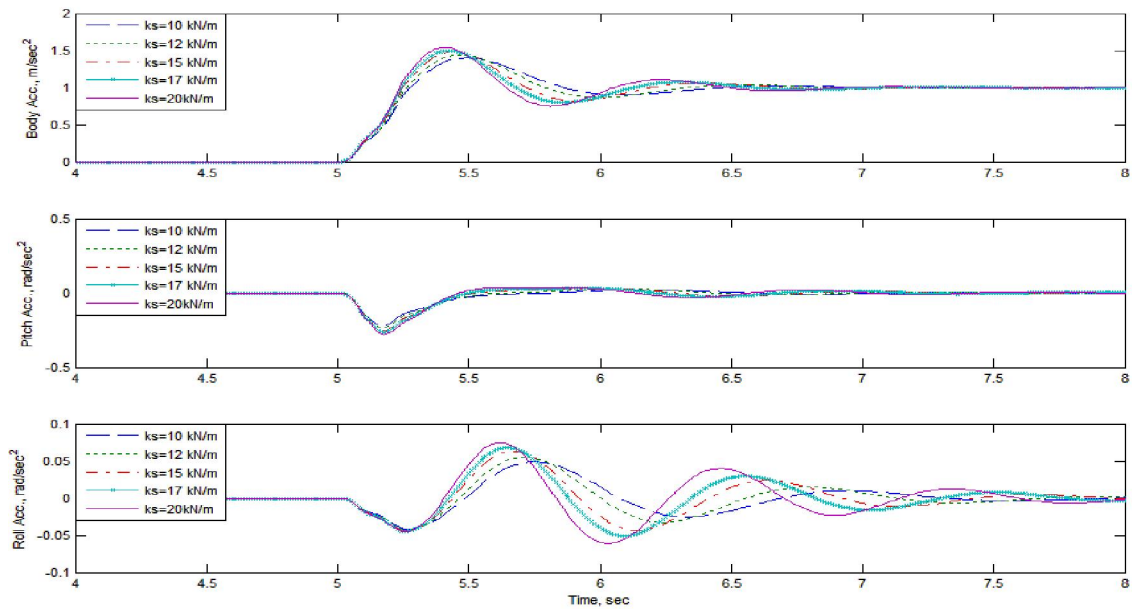


Fig.3 passive system body, pitch and roll accelerations with different springs stiffness.

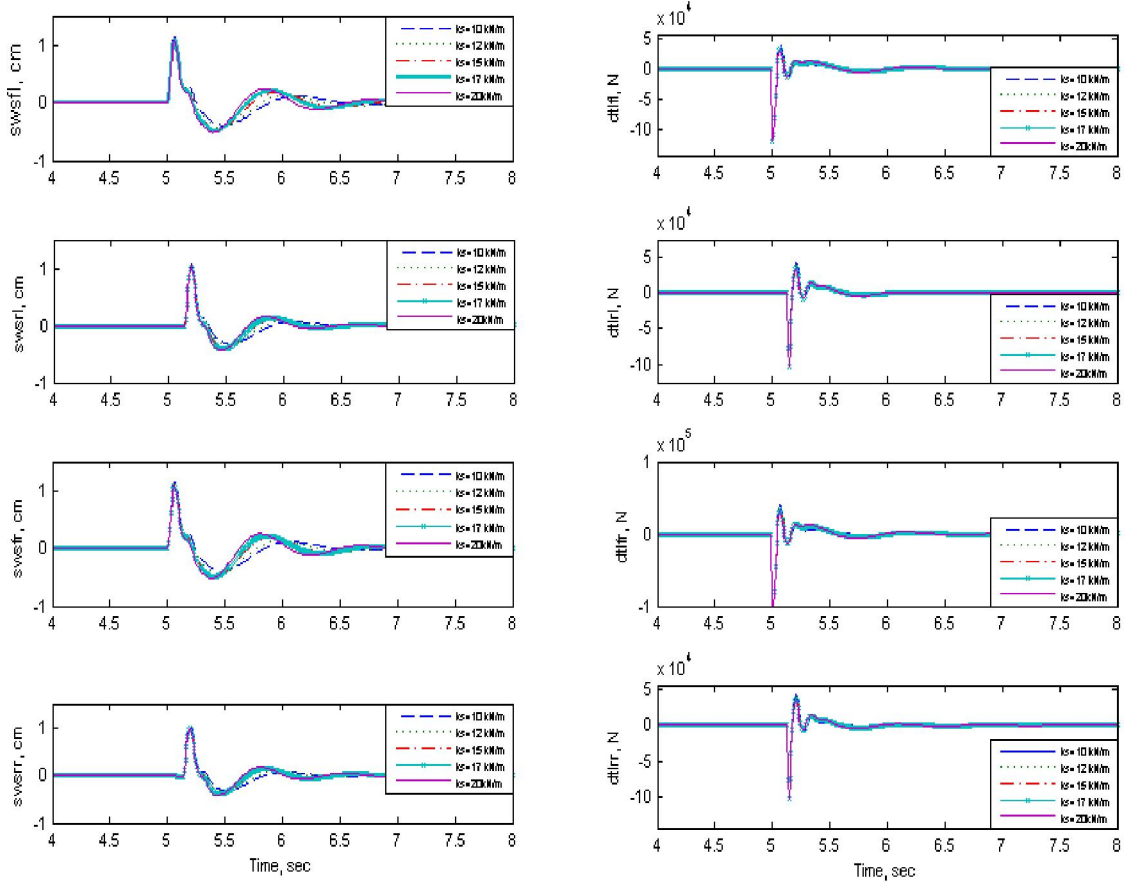


Fig 4 passive system suspensions working space and dynamic tyre loads with different springs stiffness.

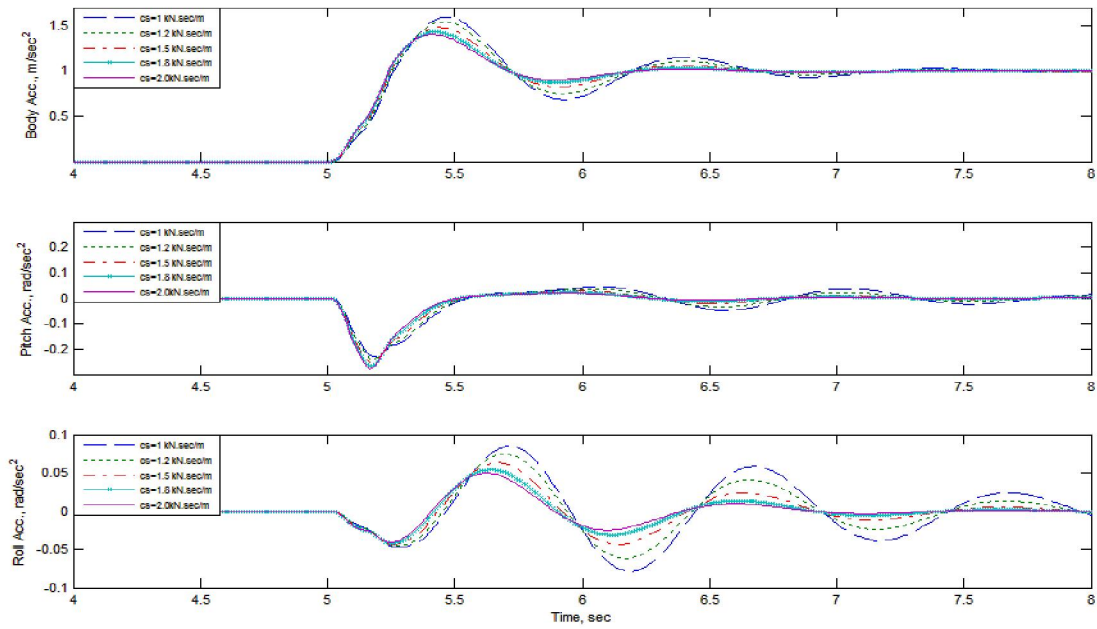


Fig.5 passive system body, pitch and roll accelerations with different damping coefficients.

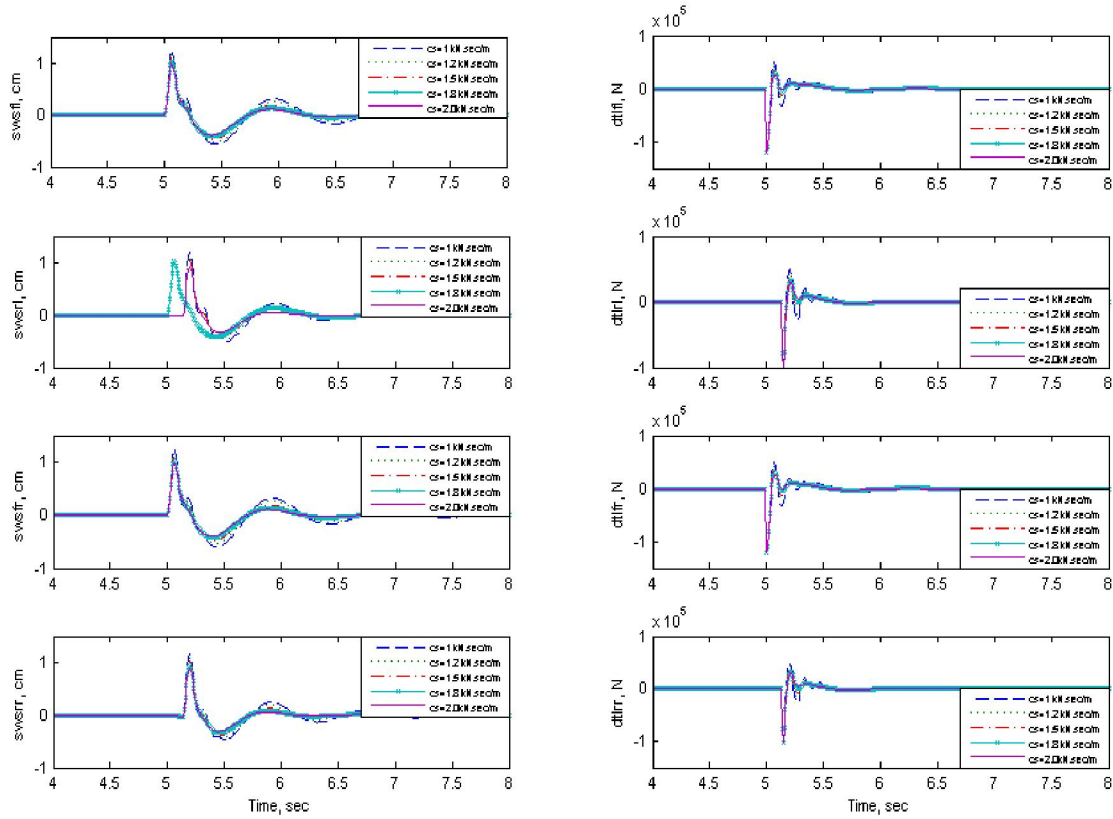


Fig.6 passive system suspensions working space and dynamic tyre loads with different damping coefficients

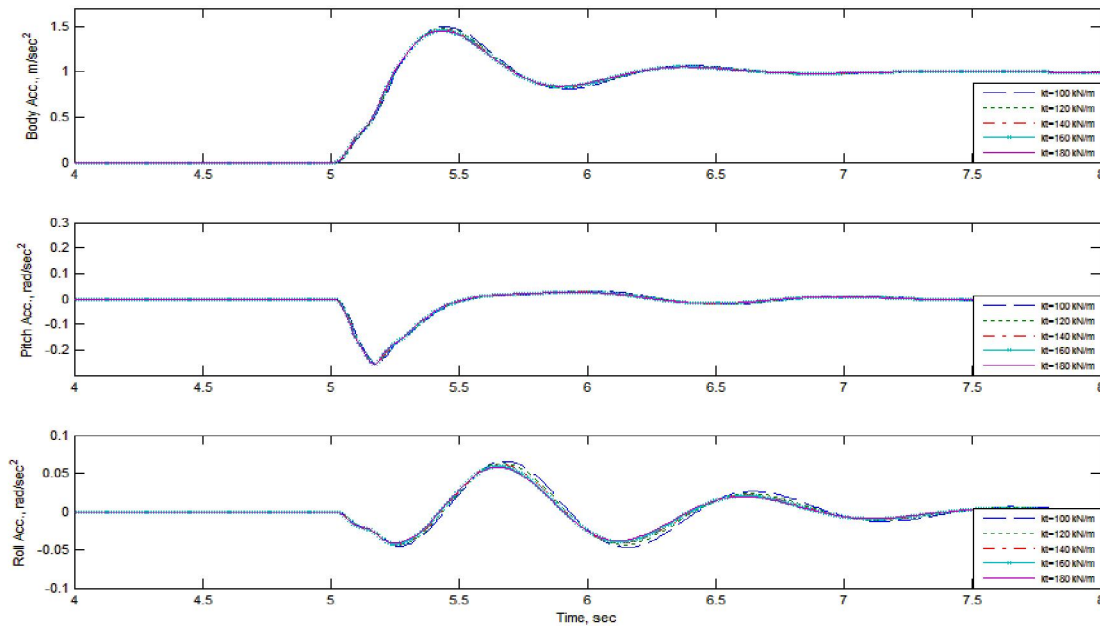


Fig.7 passive system body, pitch and roll accelerations with different damping coefficients

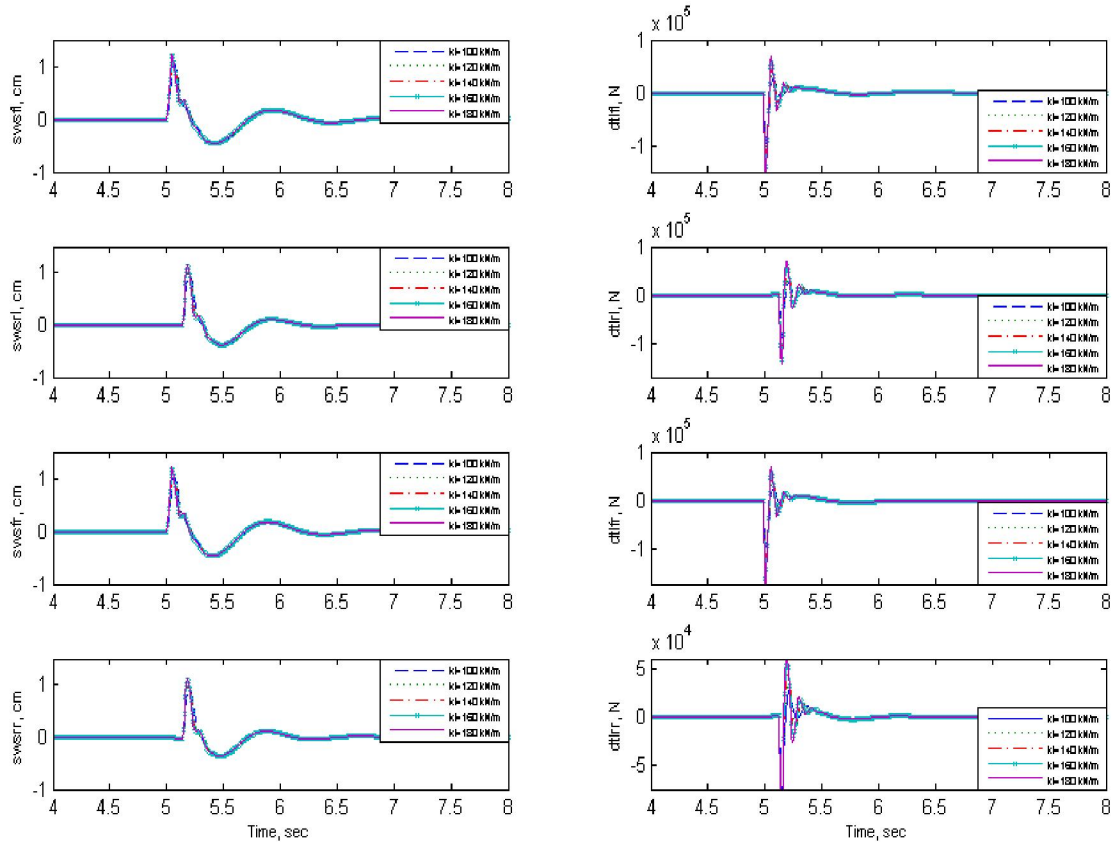


Fig.8 passive system suspensions working space and dynamic tyre loads with different tyre stiffnesses

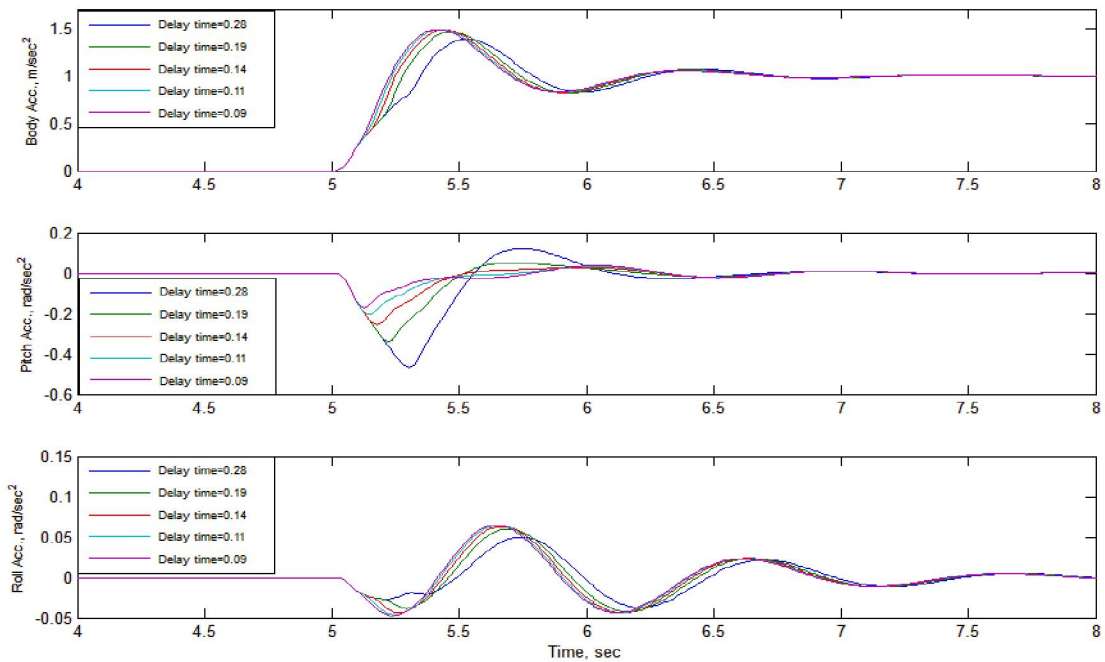


Fig.9 passive system body, pitch and roll accelerations with different delays times

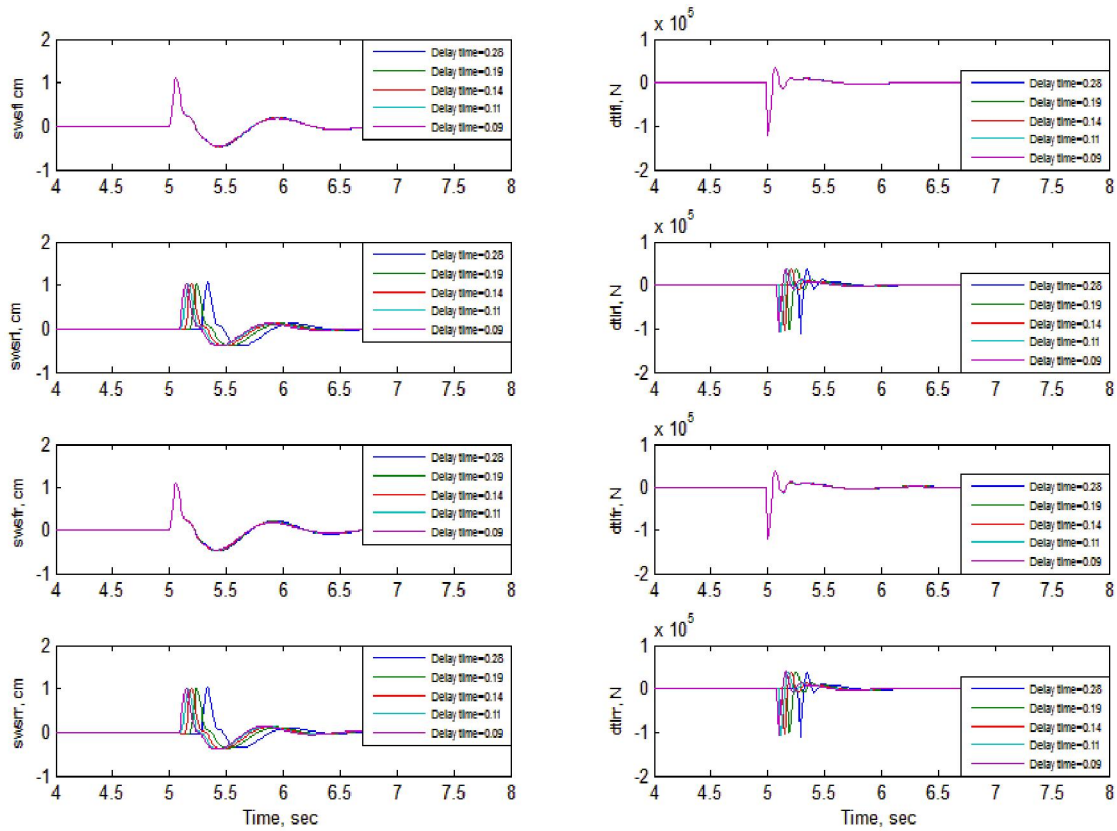


Fig.10 passive system suspensions working space and dynamic tyre loads with different delay times

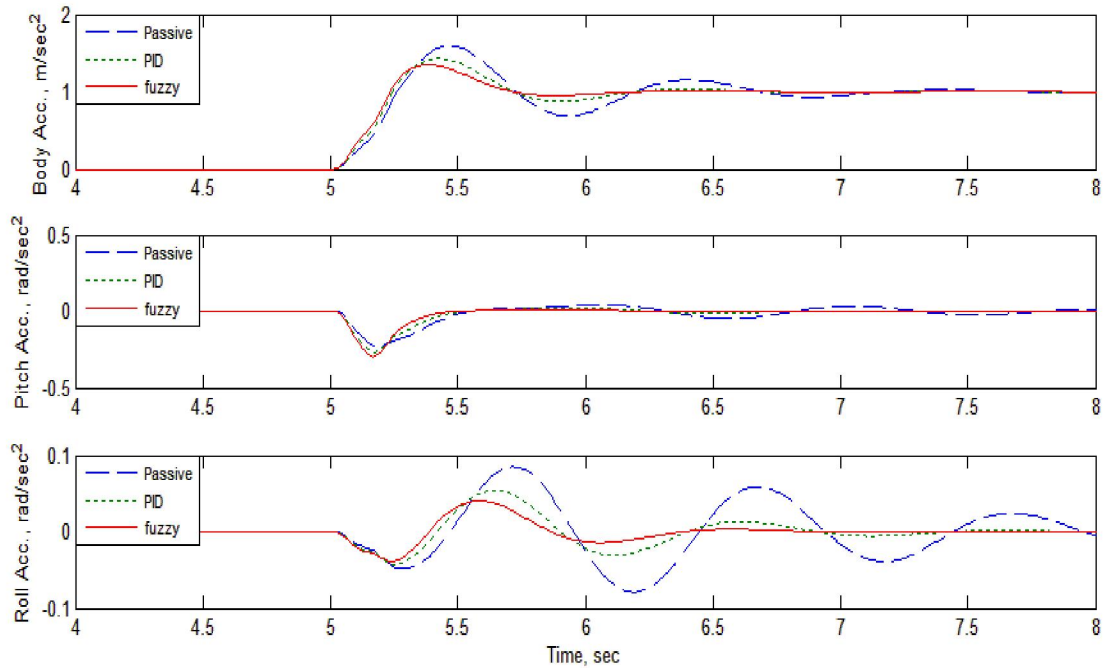


Fig.11 passive, PID control and Fuzzy control systems of body, pitch and roll accelerations



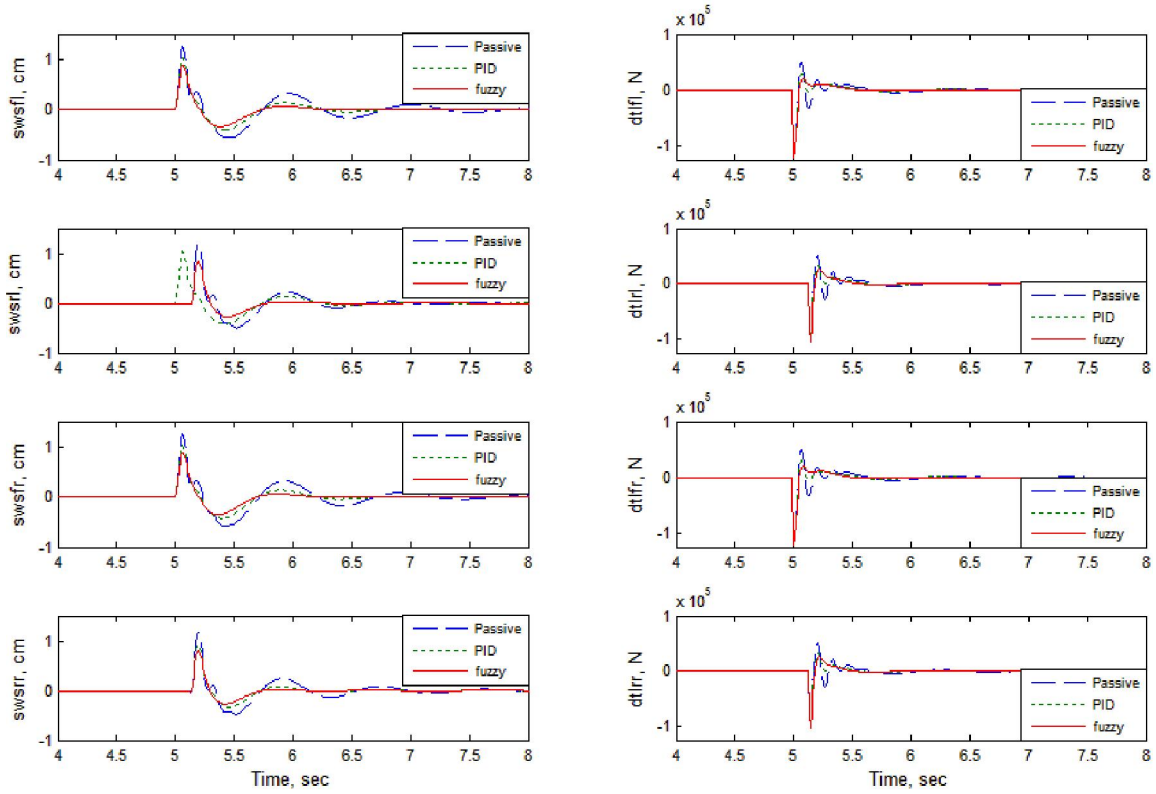


Fig.12 passive, PID control and Fuzzy control systems of suspensions working space and dynamic tyre loads

Appendix (A)

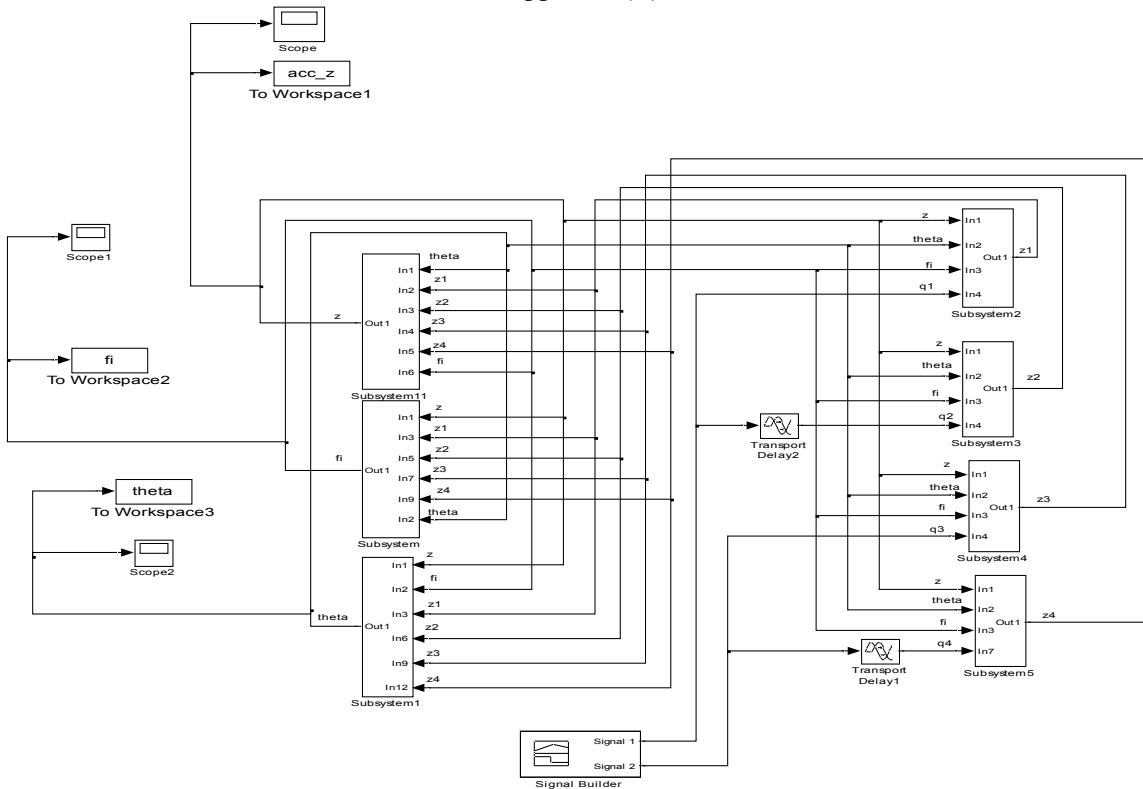


Fig. A1 Full Car Model Simulink [15]

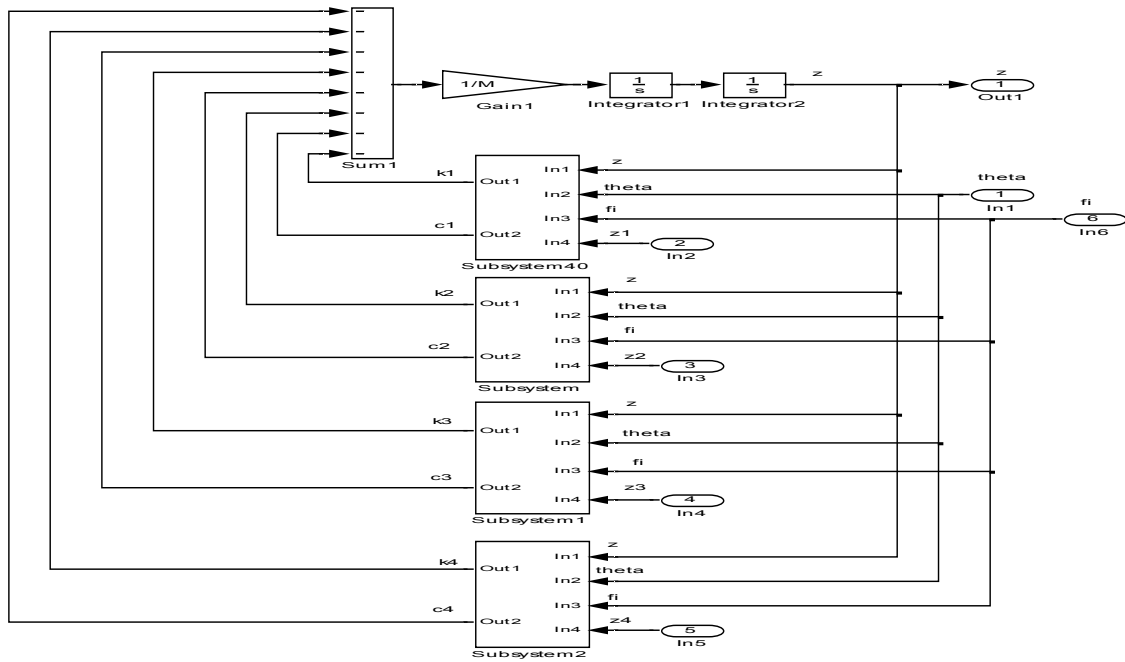


Fig. A2 Subsystem (1) for full car model Simulink (about Vertical axis) [15]

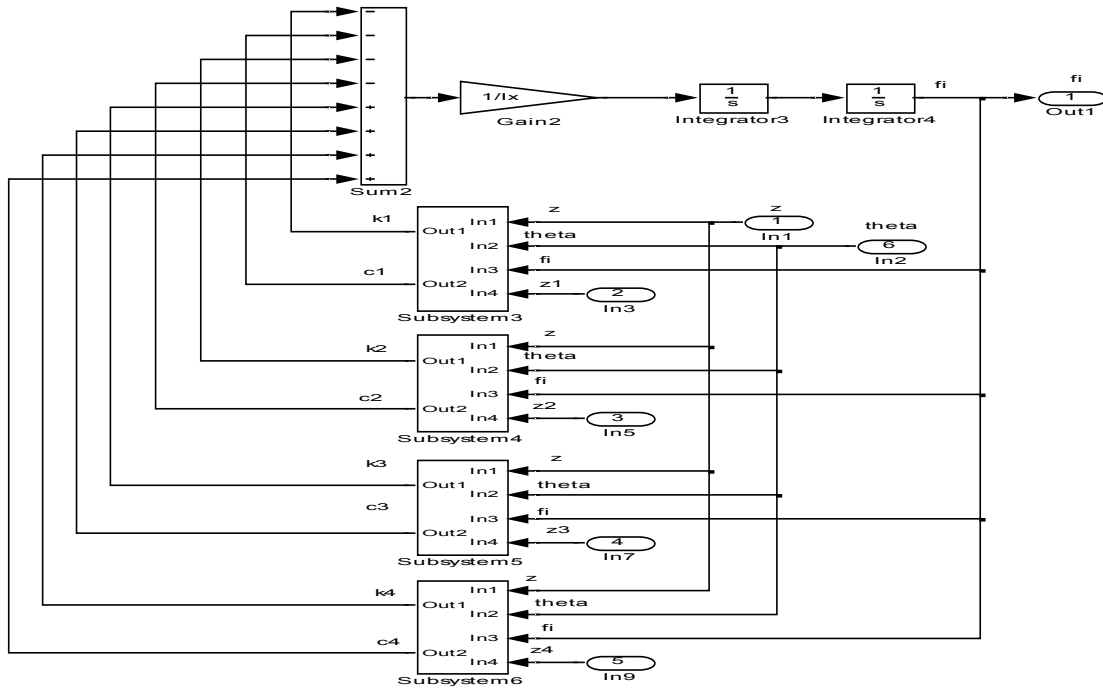


Fig. A3 Subsystem (2) for full car model Simulink (about Roll axis)[15]

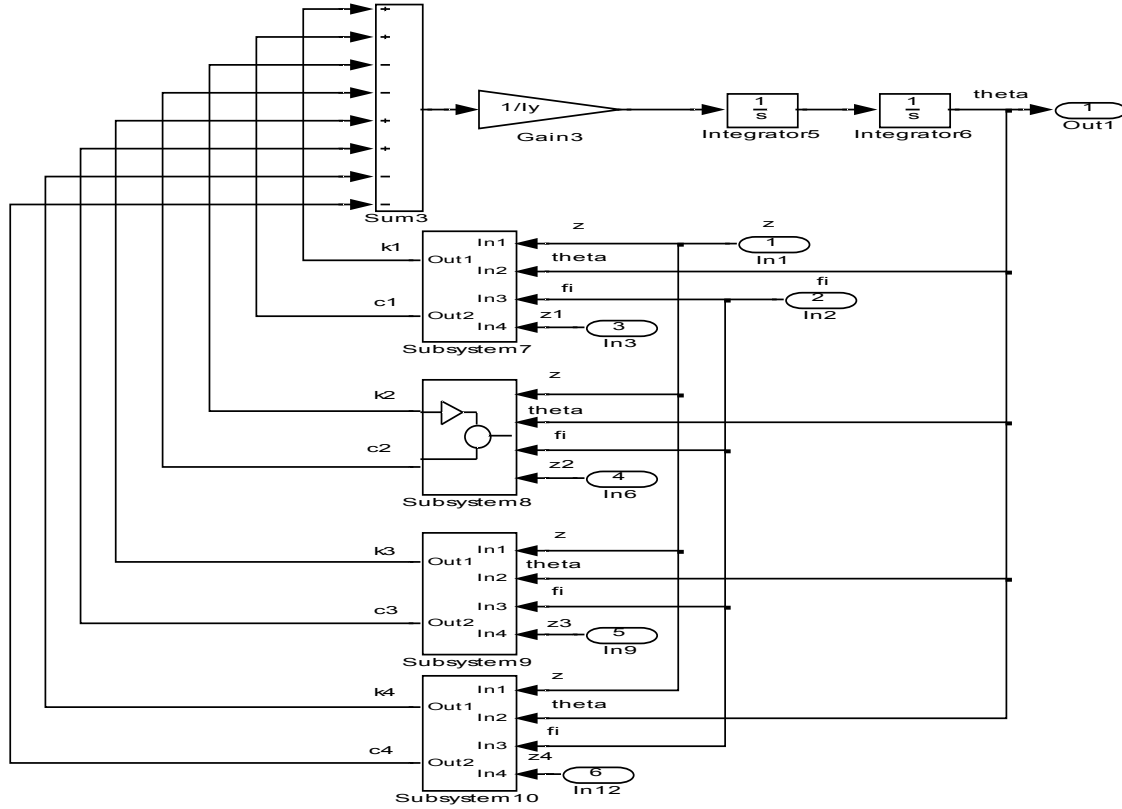


Fig. A4 Subsystem (3) for full car model Simulink (about Pitch axis)[15]

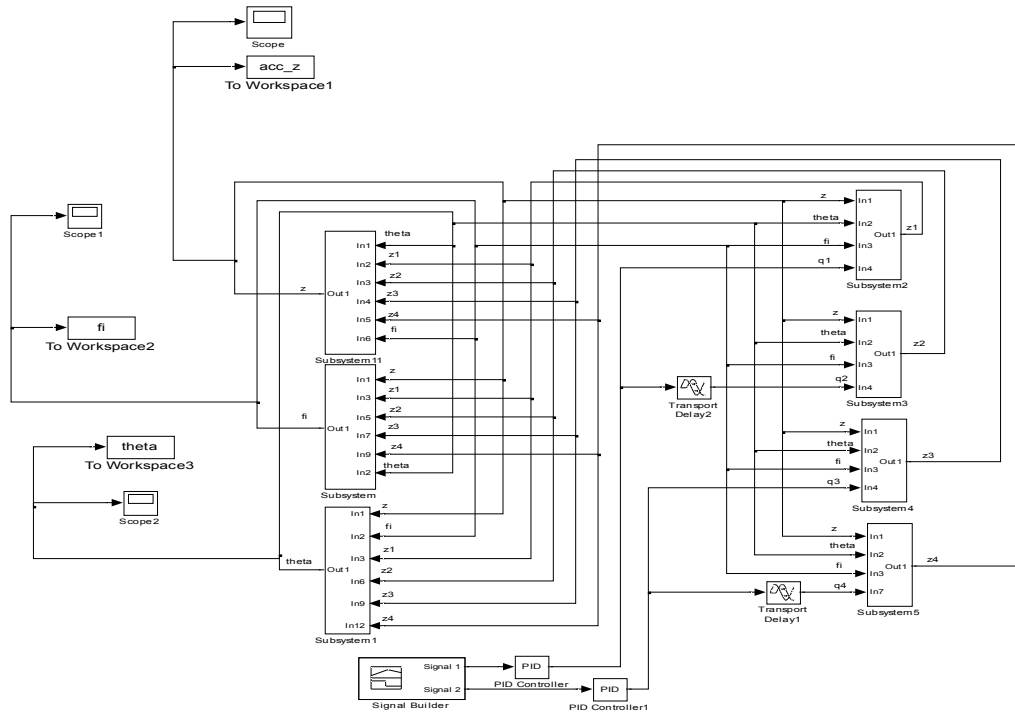


Fig. A 5 Full car model Simulink with PID Control

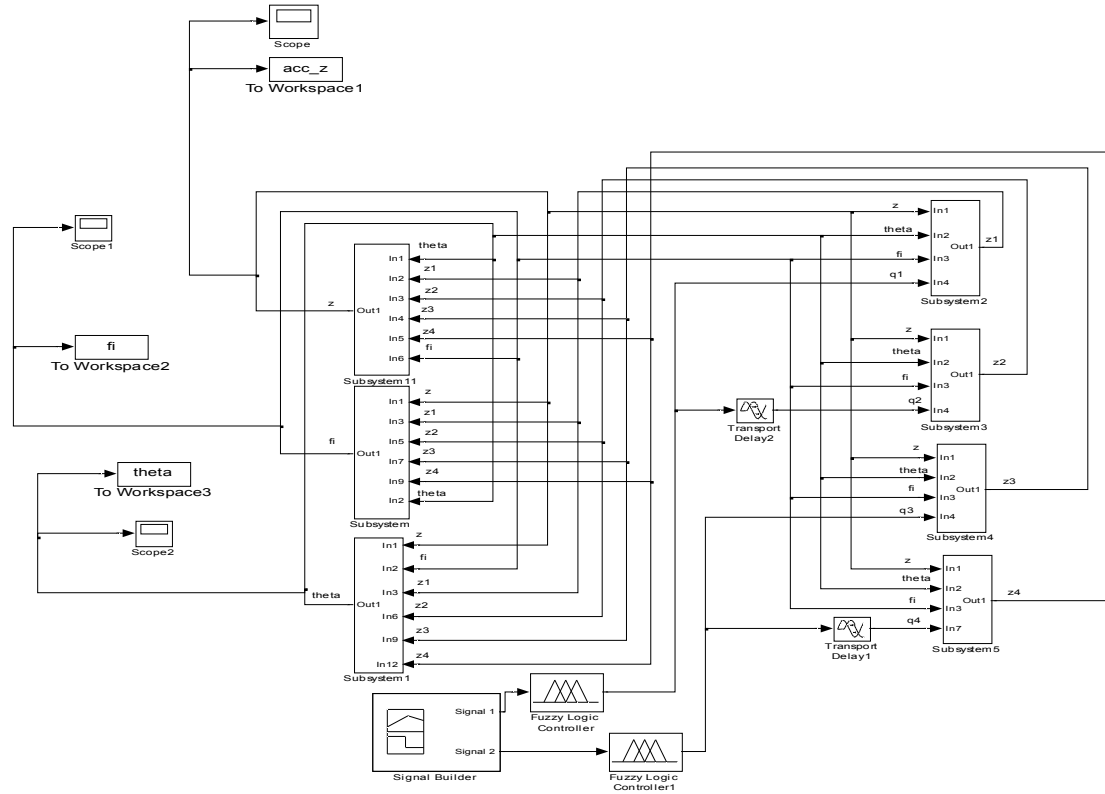


Fig. 6 Full car model Simulink with Fuzzy Control

## Conclusions

The heavy vehicle with passive suspension system consists 7-degree of freedom ride model has been developed and validated. This passive vehicle model was constructed in Simulink. These models were validated by simulating the models at different springs and tyres stiffness, damping coefficient and delay time. with an step input road. In this paper, the full car suspension system with PID and fuzzy controls is studied to achieve optimum ride. The results are summarized as A significant improvement in ride performance can be obtained using a suspension system with PID and fuzzy controls suspension systems compared with a passive suspension system.

## References

1. Moaaz A.O., Abd-El-Tawwab A.M., Abd-El-Gawaad K.A. and Ossman, A.T.A. : Characteristics of semi-active suspension system, The Bulletin of the Faculty of Eng. & Tech. Minia University, Minia, Egypt, Vol., No., Dec., 2011
2. Ayman A. Aly, H. Ohuchi and A. Abo-Ismael. A Cross Coupled Intelligent Fuzzy Controller of A 2 DOF Electro-Hydraulic Servo System, Conference of Fluid Power System, Akita, JAPAN, 2000.
3. Chong-zhi Song and You-qun Zhao." Fuzzy Multi-Objective Optimization of Passive Suspension Parameters" Journal of Fuzzy Information and Engineering , Vol. 2, No. 1, pp. 87-100, 2010.
4. Zheng Yinhuan "Research on fuzzy logic control of vehicle suspension system" Mechanic Automation and Control engineering (MACE), 2010 International Conference onDate of Conference: 26-28 June 2010, Sch. of Mech. & Electr. Eng., Wuhan Univ. of Technol., Wuhan, China, pp 307 – 310.
5. Titli, A. and Roujeh S. "Design of active and semi-active automotive suspension using fuzzy logic" proceeding of the 12 Triennial world congress of the international federation of automatic control Vol. 3 pergamon Oxford, UK, 1995 pp 73-77.
6. Abu-Khudhair, R. Muresan, S.X. Yang, "Fuzzy control of semi-active automotive suspensions", in *Proc. of IEEE Int. Conf. on Mechatronics and Automation*, vol. 54, no. 4, pp. 1937-1945, 2009.
7. Sanchez-Solano S., A.J. Cantera, I. Baturone, F.J. Moreno-Velo, and M. Brox, "FPGA implementation of embedded fuzzy controllers for robotic applications", *IEEE Transactions on*

- Industrial Electronics*, vol. 54, no. 4, pp. 1937-1945, 2007.
8. Dali Wang, and Ying Bai, "Implementation of fuzzy logic control systems", Springer, London, 2006, pp. 37-52.
  9. Sulaiman N., Z.A. Obaid, "FPGA-based fuzzy logic: design and applications - a review", *IACSIT International Journal of Engineering and Technology*, vol. 1, no. 5, pp. 491-502, Dec. 2009.
  10. Aranguren G., L.A.L Nozal, X. Basogain, J.L. Matin, J.L. Arroybe, "Hardware implementation of a pipeline fuzzy controller and software tools," *Fuzzy Sets and Systems*, vol. 128, no.1, pp. 61-79, 2002.
  11. Vuong P.T, A.M. Madni, and J.B. Vuong, "VHDL implementation of a fuzzy logic controller," *in Proc. of IEEE World Automation Congress*, Budapest, Hungary, 2006, pp. 1-8.
  12. Samin P.M., H. Jamaluddin, R.A. Rahman, S.A.A. Bakar, K. Hudha, "Modeling and Validation of a 7-DOF Full Car for Ride Quality," *CADME07*, Putra Brasmana Hotel, Kuala Perlis, Malaysia, 25-26 Oct.2007.
  13. Cheng C.P., C.H. Chao, T.H Li, "Design of Observer-Based FuzzySliding-Mode Control for An Active Suspension System With Full-CarModel," *Systems Man and Cybernetics (SMC), 2010 IEEE InternationalConference*, pp.1939-1944, 10-13 Oct. 2010.
  14. Darus R., Y.M. Sam, "Modeling and Control Active Suspension Systemfor A Full Car Model," *Signal Processing & Its Applications, 2009. CSPA 2009. 5th International Colloquium*, pp.13-18, Kuala Lumpur, Malaysia, 6-8 March 2009.
  15. Fuzzy logic toolbox for use with matlab, 2012.

12/2/2013