VEHICLE RIDE CONTROL USING HUMAN BODY DYNAMIC SIMULATION

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Abstract: The aim of this study was Vehicle ride control using human body dynamic simulation. When designing suspension system in ordinary sedans, we cannot only consider comfort and stability criteria. In these occasions, according to the working class of the vehicle, criteria of comfort and stability together and with a certain proportion will intervene in the designing suspension system. Principally, in such occasions, we lose the benefits of mentioned criteria due to relative consideration of the other criterion. What has been investigated in this research is the design of a controller that decreases acceleration caused by vibrations transmitted to the human body and also lowers the displacement of the tire with respect to the road. The proposed model for the body is a model with four degrees of freedom and the proposed model for the vehicle is a model with seven degrees of freedom. The proposed controller is an optimal-fuzzy controller that optimal controller and fuzzy one have been used for the design of state feedback and the change in the weighting functions of optimal controller, respectively. To confirm the strength of the designed controller, the various inputs of the actual road with varying vehicle speed have been applied to the model. The obtained results show that this controller has a major influence on deceleration transferred to the body and also in critical situations results in reduction in the displacement of the tire with respective to the road input.

Keywords: Semi-active suspension, State feedback, Fuzzy logic, Simulink, Bounce acceleration, Biodynamic models of human

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INTRODUCTION

Work on the design of active suspension systems has been started at the late 1960s. One of the first things performed in this area has been design of anti-roll systems by Meiry and Roseler in 1968 in MIT University [1]. Two issues of ride comfort and lateral stability must be considered in designing inactive suspension system. But the reality is that these two are in conflict with each other in such a way that for improvement of ride comfort the suspension system component must be selected soft but for improvement of the lateral stability the suspension system components must be selected hard. Therefore, in most cases, in the design of inactive suspension system the attempt is that a compromise point is achieved. William in 1997 investigated vehicle behavior in inactive state using 4/1 model. He obtained the vibratory response of the model using the conversion function of 1/4 model by applying road inputs randomly and then compared vibratory behavior of inactive system in various states by changing shock absorber damping coefficient and spring stiffness factor. William in another study in 1997 investigated various types of suspension systems from aspect of separating low and high frequencies exerted by the road and from an industrial aspect he designed an operator for active suspension system using gas or oil springs. In this case, the applied control method has been optimal [2]. Purdy& Bulman in 1997 have exerted 1/4 model for designing active suspension system on the racing vehicles. The presented work has been investigated from both theoretical and practical aspects. The open-circuit response control test has been performed to verify the model. In this research, we tried to work on the suspension system so that it answers properly in both low and high frequencies of the road [3]. It is worthy to note that the dynamics of an vehicle is a rapid one and it is necessary to use methods and control algorithms that can control the system at the least possible time. We can name some various methods of controlling the active suspension systems used in most of the papers in order of time progress that are as follows:

1) Classic controllers
2) Optimal control methods
3) Advanced controllers such as fuzzy and neural networks

Rao and Prahlad in 1995 have used linear 1/4 model for designing active suspension system of the vehicle. They used sky-hook damping model in their study. Fuzzy controller has been used in this work in which location change of suspension system (the difference between the location of center of sprung and unsprung mass) and sprung mass velocity have been considered as fuzzy controller inputs and the output of fuzzy system is changes of the control force. In this paper, bell membership functions for linguistic variables of suspension system displacement and sprung mass velocity and change of control force has been used. The road profile used in this paper has been pseudo-random one with natural frequencies of 1 and 2 Hz. The results of this paper are so that the acceleration of the body in the active suspension system model has been less than that of the reference model. Also, to check the strength of the controller with increased sprung mass by 30% and also decreased stiffness of the suspension system by 30%, the results have not changed. This issue shows capability of fuzzy systems to face with many changes [4]. Yoshimura et al. in 1999 used nonlinear 1.2 model for designing active suspension system. In this model, spring stiffness coefficients and shock absorber damping factors are nonlinear.

The purpose of this paper has been to decrease bounce acceleration and acceleration of pitch acceleration. Because of being overwhelming to design a type of controller for such a nonlinear system, so we have used a combination of a linear controller and fuzzy one as a complementary controller. Control forces are created by means of acting pistons in a hydraulic cylinder. The linear part of this controller is for controlling bounce acceleration that bounce acceleration feedback has been used in front and back suspension location. The road input has been randomly considered in this work [5]. Considering MacPherson suspension system for designing active suspension system Amato and Viassolo in 2000 have applied 1/4 model. The model and the operator used in this paper were linear and nonlinear, respectively. The purpose of doing this work is to decrease bounce acceleration for ride comfort and preventing the collision of suspension system components during control and maintaining life time of suspension system components. The proposed controller has been composed of two rings which inner ring controls hydraulic operator for tracing optional acting force and outer ring is a fuzzy controller that makes the controller update for creating optional operating force [6]. Tzuu-hseng et al. in 2000 use 1/4 model for designing an active suspension system. They used a combination of two fuzzy controllers in their paper. This controlling design includes of a fuzzy feedback controller and a fuzzy feed forward one. Fuzzy feedback controller has been used for a compromise between ride comfort and tire displacement with respect to the body based on speed variations of sprung and unsprung masses and fuzzy feed forward controller has been applied to eliminate the road disturbances. The purpose of proposed controller is to create ride comfort and stability for the vehicle on the rough roads [7]. Following Yoshimura, Fan and Jun in 2001 applied nonlinear 1/2 model for designing active suspension system. Their purpose was to decrease bounce acceleration and pitch acceleration. In this paper, a combination of linear controller and fuzzy one have been used a complementary controller. But the difference between this work and Yoshimura's work is that a PID controller has been used for controlling bounce acceleration instead of using bounce acceleration feedback. The obtained results are resulted from control system improvement with respect to Yoshimura's work [8]. Daniel Fischer and his colleague in 2004 used Mechatronics methods to estimate and control active and semi-active suspension systems and tested the results on experimental models and implemented them on the real vehicle [9]. Els et al. in 2007 investigated compromise determination method between ride comfort and stability on the military vehicles. In this paper three types of military vehicles have been investigated and good results have been obtained for practical designing on suspension system of military vehicles [10]. Guclu and Gulezb in 2009 used one degree of freedom body model on the seven degrees of freedom vehicle model and designed an operator under driver's seat using neural network that greatly decreases bounce acceleration entered to the body [11]. Solomon in 2011 designed a gas damper with variable coefficient on the suspension system of real freight vehicles. He showed in this paper that bounce acceleration can be decreased while stability criteria do not achieve critical situations [12].

As we can see in previously performed works, in most modeling, a vehicle model and in some cases with simple body model has been used to design suspension system. In papers in which body model has been used on the vehicle model, an operator under driver's seat has been embedded.

In direction of doing this research, a combination of seven degrees of freedom vehicle model and four degrees of freedom body model (that is one of the most presented models for the body) have been applied for designing semi-active suspension system , their results have been compared with vehicle model without considering human body model. Also, the operator under driver's seat has been omitted in previously performed papers and the exerted force to the passenger has been provided using available operator in suspension system. The final purpose of this research is to control bounce acceleration of the human body and tire displacement with respect to the road but as we know two issues of ride comfort and tire displacement with respect to the road are in conflict with each other. In this study, depending on vehicle performance situations, we aim to create the optional force in the suspension system. For this purpose, an optimal controller and a fuzzy one have been used to improve ride comfort and tire displacement with respect to the road and to create compromise between these two issues depending on vehicle performance situation, respectively. To control the acceleration of human body and tire displacement with respect to the road, a state feedback designed based on one of the optimal control methods has been applied. Weighting functions used in optimal controller are constant numbers that by selecting them we can improve one of these two issues. Applying a fuzzy controller we can improve the acceleration of the human body or tire displacement with respect to the road in proportion with various vehicle performance situations by changing in weighting functions used in optimal controller. To explain clearly designing optimal and fuzzy controllers, at first, 1/4 vehicle model with one degree of freedom human body have been used and then complete vehicle model and human body were used. The inputs of fuzzy controller are vehicle speed and root mean squares (RMSs) of the acceleration of vehicle body and its output is weighting functions used in state feedback. The road profile used in this thesis is a sinusoidal one, lump, and type B, C, and D real road. In designing semi-active suspension system, ride comfort and stability have a great importance. In this project, the purpose of control is to minimize bounce acceleration of vehicle and human body (from aspect of comfort) and also to minimize tire displacement with respect to the road input (from aspect of stability). This project includes of a state feedback that LQR method has been used to design it. Because of existence of uncertainty in vehicle system and problems related to modeling, the proposed controller in this project is an optimal-fuzzy controller. Firstly, we explain state feedback that is calculated by LQR method. For simplification of explanation of this method, 1/4 vehicle model and also one degree of freedom body model is used and in conclusion section, seven degrees of freedom and four degrees of freedom body model are applied.

Designing state feedback using LQR method [2]:

A 1/4 model with semi-active suspension system with a focused mass representing one degree of freedom body model is shown in figure 1. In this model, a variable damper has been used as the acting force (F_a) that according to various conditions such as type of the road provides necessary force between sprung and unsprung mass based on a control rule. Block diagram of designed controller is shown in figure 1.

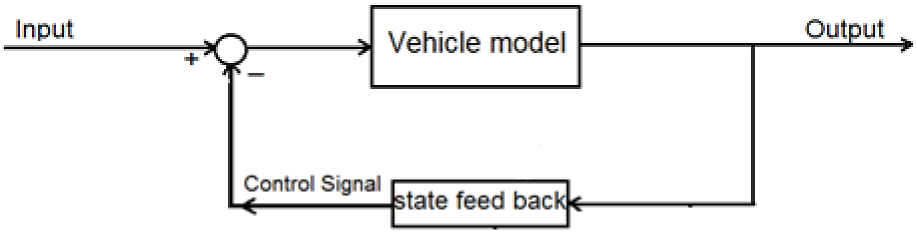

Figure 1-Block diagram of state feedback

The frequency response for different amounts of weighting functions:

A) The state that weighting functions related to the vehicle is against zero and weighting functions related to human body is equal to zero:

$$\rho_1 = 0.1 \;, \; \rho_2 = 0.1 \;, \; \rho_3 = 10 \;, \; \rho_4 = 100 \;, \; \rho_5 = 0 \;, \; \rho_6 = 0$$

B) The state that weighting functions related to the vehicle is similar to state A and weighting functions related to human body is not equal to zero:

$$\rho_1 = 0.1 \;, \; \rho_2 = 0.1 \;, \; \rho_3 = 10 \;, \; \rho_4 = 100 \;, \; \rho_5 = 10 \;, \; \rho_6 = 1000$$

Frequency response of the tire displacement with respect to the road input is given in figure 2.

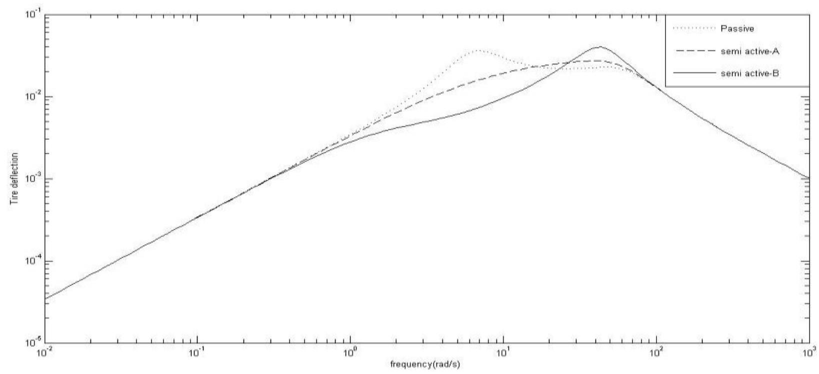

Figure 2-Frequency response of the tire displacement with respect to the road input

Frequency response of the acceleration of vehicle body is presented in figure 3.

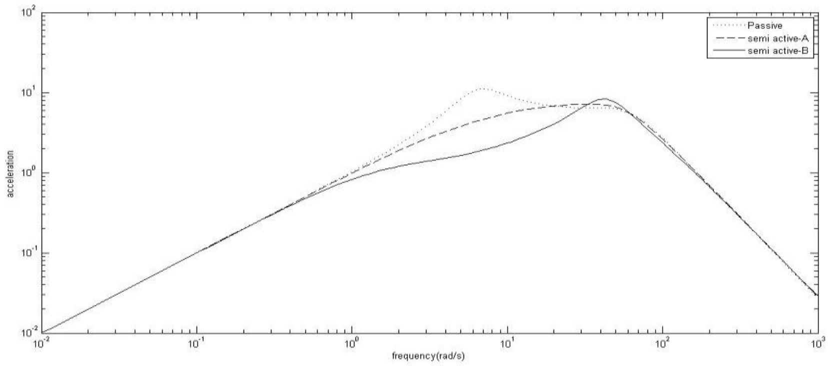

Figure 3-Frequency response of the acceleration of vehicle body

Frequency response of the acceleration of human body is shown in figure 4.

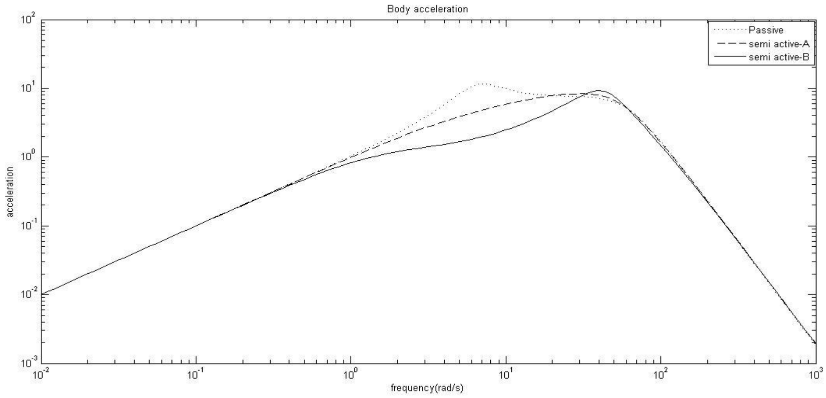

Figure 4-Frequency response of the acceleration of human body

It is must be considered that the behavior of the acceleration of human body and vehicle body are very close to each other at different frequencies. As can be seen, we can decrease the accelerations of the human body and vehicle body at frequencies 1 to 5 Hz using body model and applying weighting functions for it and also we can improve stability but at frequency of 10 Hz, the acceleration and stability become undesirable. To tailor the acceleration and stability at frequency of 10 Hz, we must increase weighting functions related to the tire.

C) We increase weighting functions related to the tire displacement with respect to the road.

$$\rho_1 = 1000000, \ \rho_2 = 0.1, \ \rho_3 = 10, \ \rho_4 = 100, \ \rho_5 = 10, \ \rho_6 = 1000$$

Frequency response of the tire displacement with respect to the road input is depicted in figure 5.

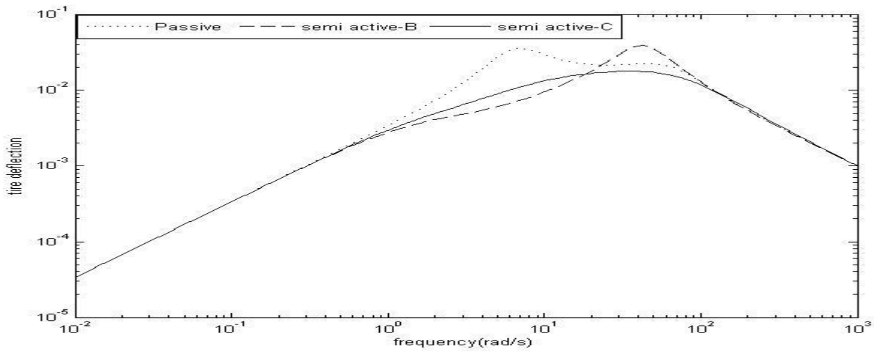

Figure 5-Frequency response of the tire displacement with respect to the road input

Frequency response of the acceleration of vehicle body is presented in figure 6.

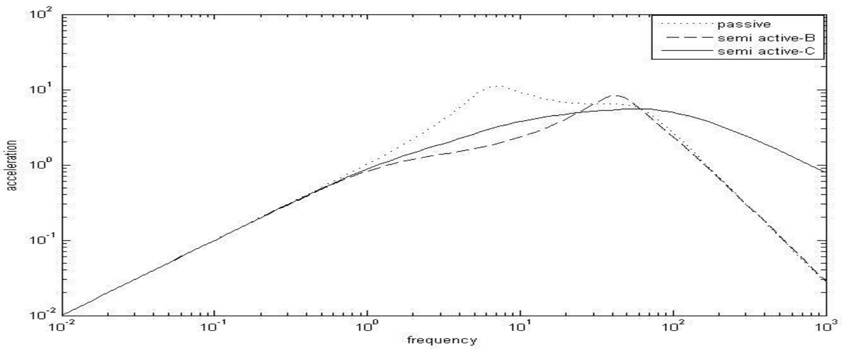

Figure 6-Frequency response of the acceleration of vehicle body

Frequency response of the acceleration of human body is shown in figure 7.

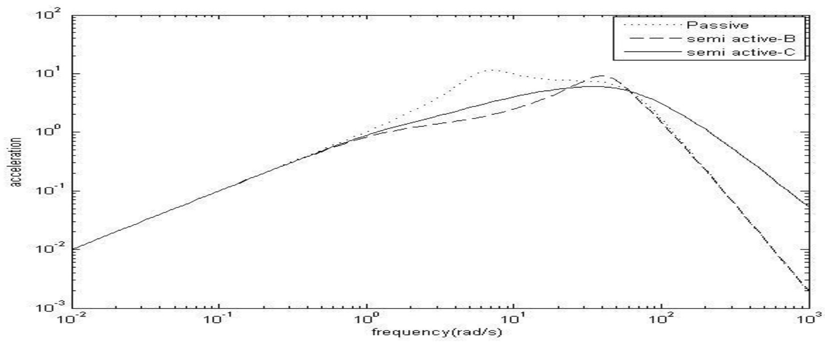

Figure 7-Frequency response of the acceleration of human body

As can be seen in the curves, with enhancement of weighting functions related to the tire, stability and acceleration are improved in frequency of 10 Hz but acceleration has been undesirable at frequencies higher than 10 Hz.

Response to sinusoidal input:

To mentioned contents be clearer, we use a sinusoidal input with frequencies of 1 and 10 Hz.

Sinusoidal input with a frequency of 1 Hz ($z_r = 0.0125\sin(2\pi \times t)$):

Tire displacement with respect to the road input, the acceleration of vehicle body and the acceleration of human body are given in figures 8, 9, and 10.

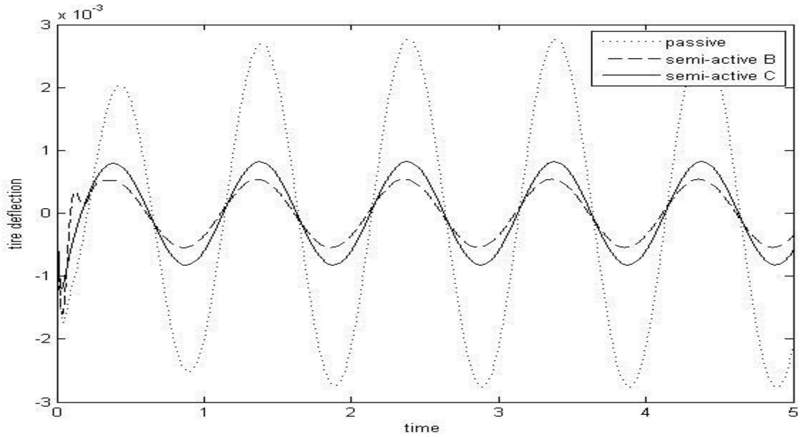

Figure 8- The tire displacement with respect to the road input

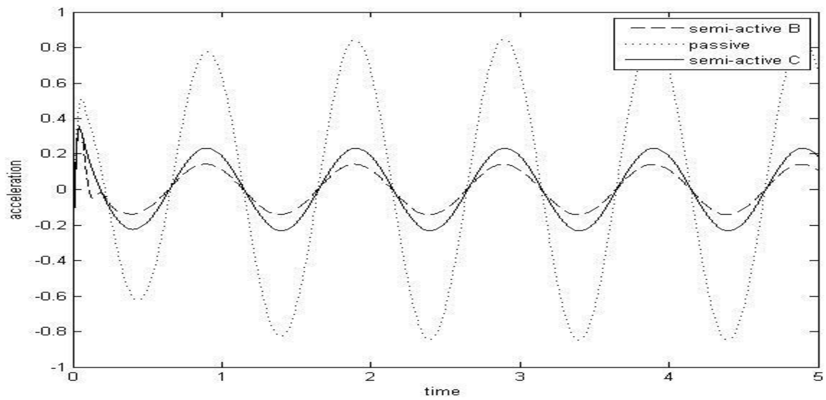

Figure 9- The acceleration of vehicle body

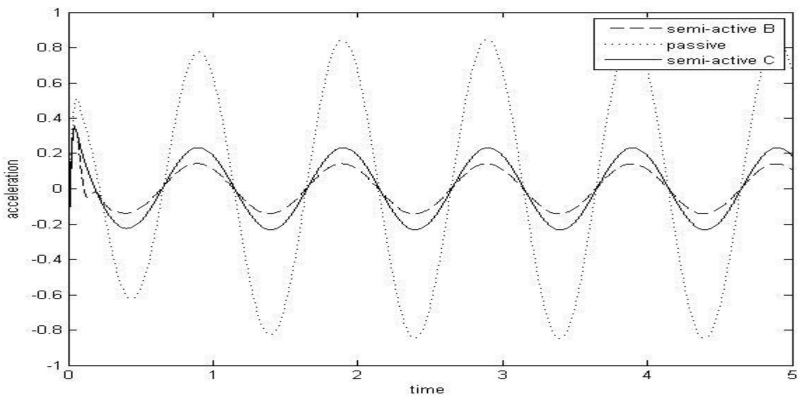

Figure 10- The acceleration of human body

Sinusoidal input with a frequency of 10 Hz ($z_r = 0.0125\sin(20\pi \times t)$):

Tire displacement with respect to the road input, the acceleration of vehicle body and the acceleration of human body are given in figures 11, 12, and 13.

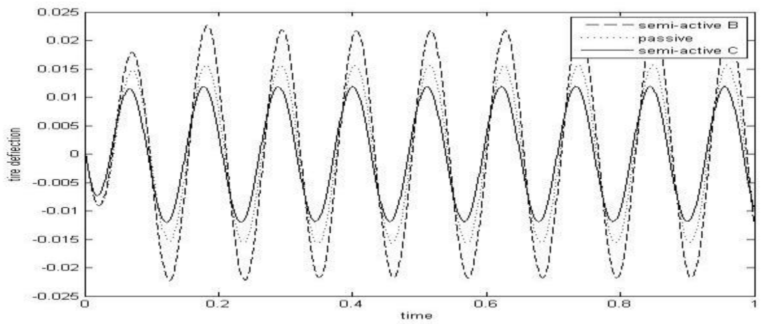

Figure 11- The tire displacement with respect to the road input

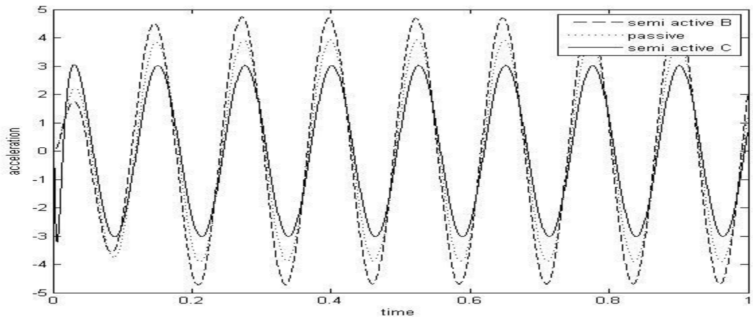

Figure 12- The acceleration of vehicle body

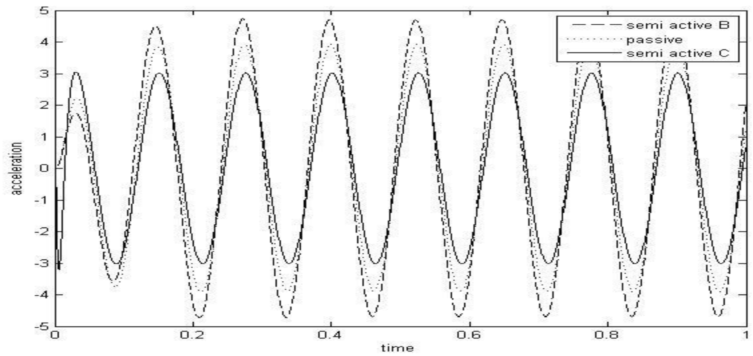

Figure 13- The acceleration of human body

As can be seen in the curves, with enhancement of weighting functions related to the tire, stability and acceleration are improved in frequency range of 10 Hz but acceleration has been undesirable at frequencies higher than 10 Hz.

Response to real road:

We know that real road input is random and without a constant frequency. Therefore, we in this section apply type B road like figure 14 as the input for the model and show its curves. It is necessary to note that vehicle speed has been considered 20 m/s.

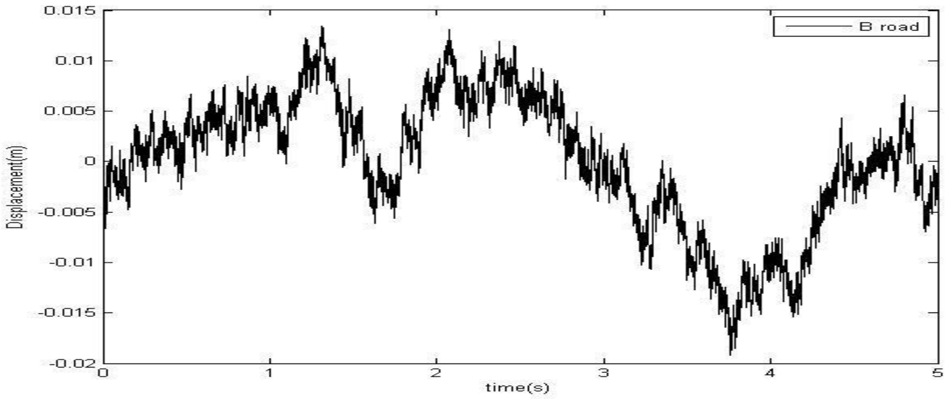

Figure 14-Type B road

Firstly, we apply type B road input to the semi-active suspension system with many weighting functions for acceleration and as we will observe acceleration of semi-active suspension system is better than that of the inactive suspension system but the tire displacement with respect to the road becomes undesirable.

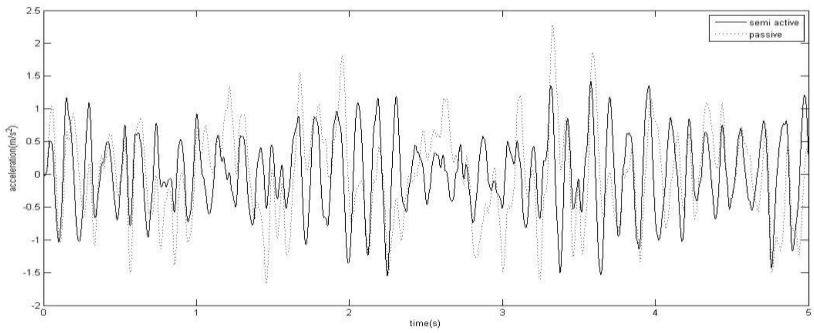

Figure 15- The acceleration of human body

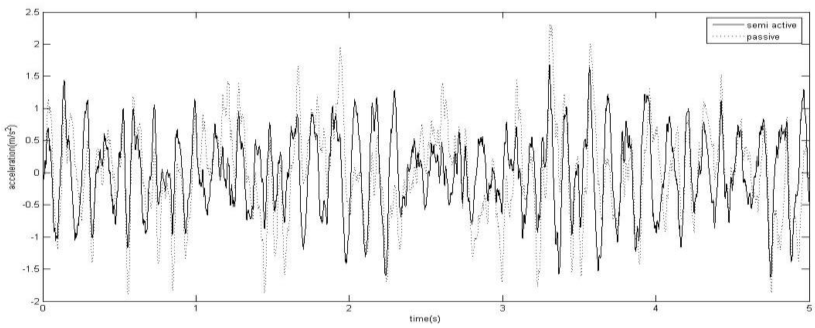

Figure 16- The acceleration of vehicle body

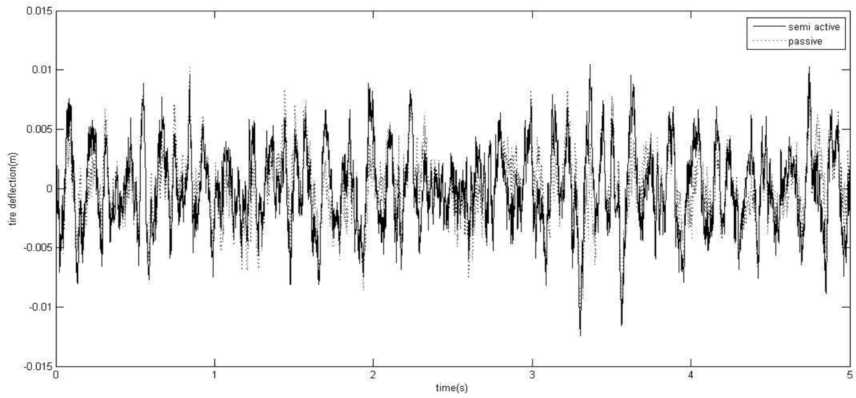

Figure 17- The tire displacement with respect to the road input

Now we apply type B road input to the semi-active suspension system with many weighting functions for tire displacement and as we will see tire displacement with respect to the road finds a desirable situation in semi-active suspension system but the acceleration becomes undesirable.

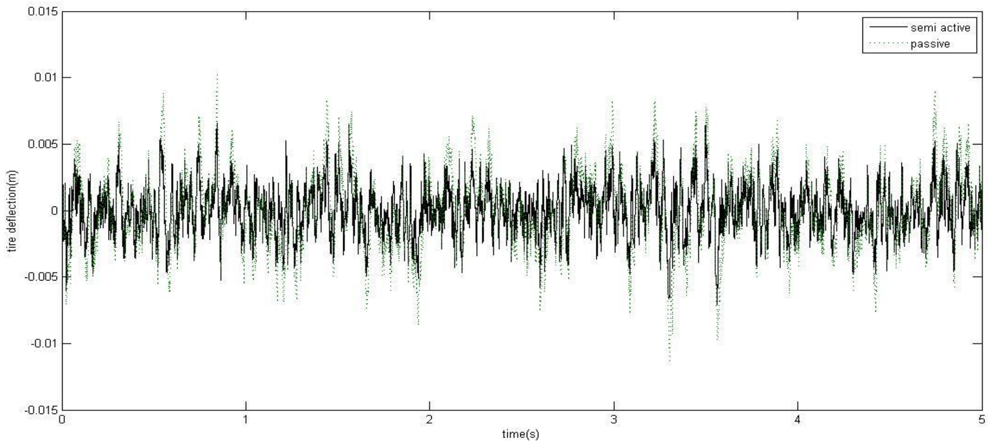

Figure 18- The tire displacement with respect to the road input

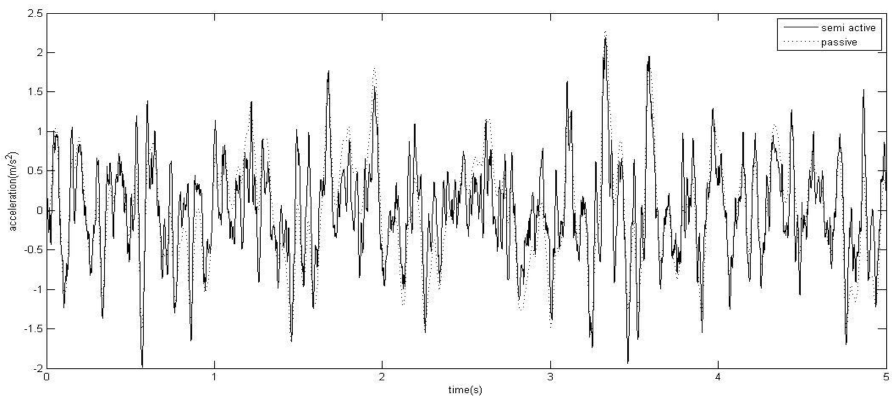

Figure 19- The acceleration of human head

As it is clear from the curves, due to conflict in two important issues of ride comfort and stability, we can only improve one of them; however, with improving one of them, the other one will find an undesirable situation. So, the best solution is to improve ride comfort or tire displacement with respect to the road depending on the condition of vehicle performance. This has been performed by changing optimal controller weighting functions using a fuzzy controller in this thesis. Fuzzy controller input is the summation of root mean squares (RMSs) of vehicle body acceleration and vehicle speed and the output of fuzzy controller of weighting functions used in the controller is optimal.

Seven degrees of freedom vehicle model and body model:

In this section, we give figure 20, equations and definition of state variables for complete model.

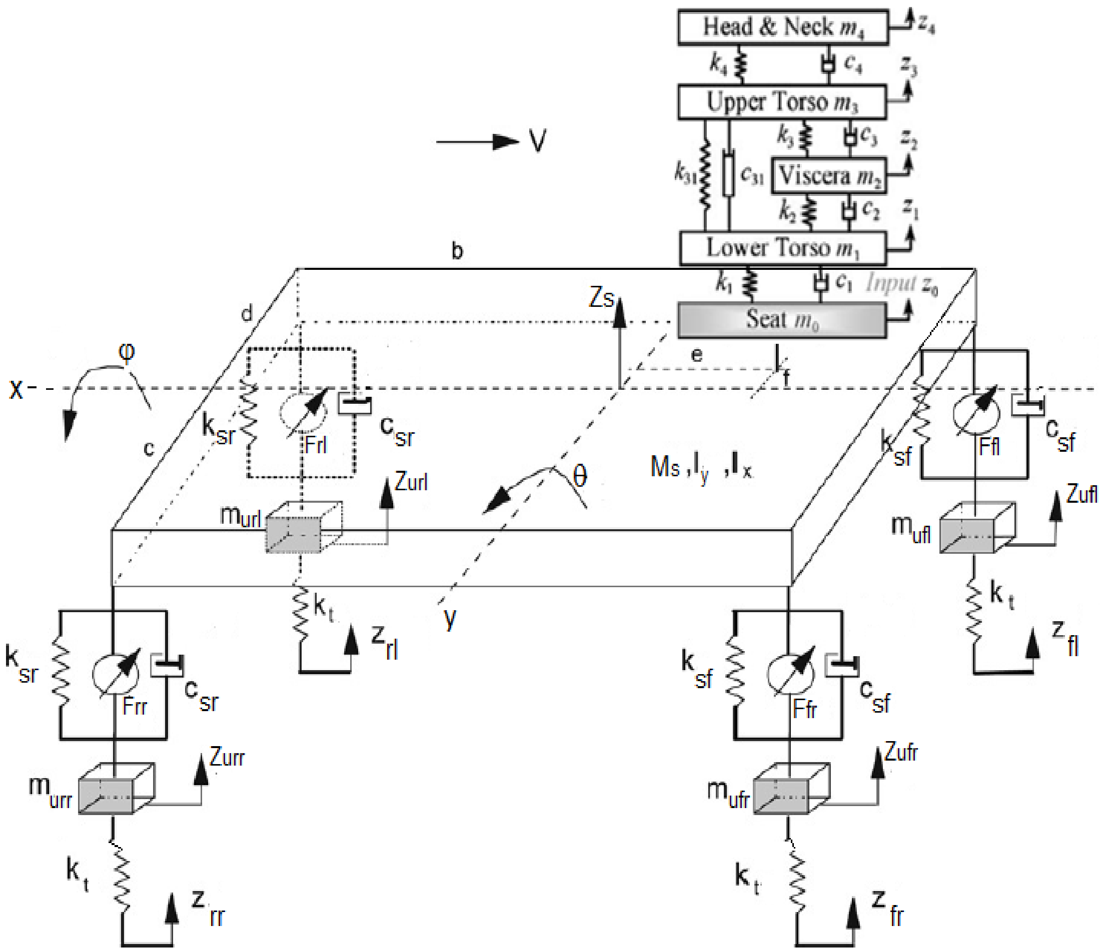

Figure 20- Seven degrees of freedom model and body model

$$m_1\ddot{z}_1 = -(k_1 + k_2 + k_{31})z_1 - (c_1 + c_2 + c_{31})\dot{z}_1 + k_2 z_2 + c_2\dot{z}_2 + k_{31}z_3 + c_{31}\dot{z}_3 + k_1 z_s + c_1\dot{z}_s + ek_1\theta + ec_1\dot{\theta} + fk_1\varphi + fc_1\dot{\varphi}$$

$$m_2\ddot{z}_2 = k_2 z_1 + c_2\dot{z}_1 - (k_2 + k_3)z_2 - (c_2 + c_3)\dot{z}_2 + k_3 z_3 + c_3\dot{z}_3$$

$$m_3\ddot{z}_3 = k_{31}z_1 + c_{31}\dot{z}_1 + k_3 z_2 + c_3\dot{z}_2 - (k_4 + k_3 + k_{31})z_3 - (c_4 + c_3 + c_{31})\dot{z}_3 + k_4 z_4 + c_4\dot{z}_4$$

$$m_4\ddot{z}_4 = k_4 z_3 + c_4\dot{z}_3 - k_4 z_4 - c_4\dot{z}_4$$

$$m_s\ddot{z}_s = k_1 z_1 + c_1\dot{z}_1 - (2k_{sf} + 2k_{sr} + k_1)z_s - (2c_{sf} + 2c_{sr} + c_1)\dot{z}_s + k_{sf}z_{ufl} + c_{sf}\dot{z}_{ufl} + k_{sf}z_{ufr} + c_{sf}\dot{z}_{ufr} + k_{sr}z_{url} + c_{sr}\dot{z}_{url} + k_{sr}z_{urr} + c_{sr}\dot{z}_{urr} - (2ak_{sf} + 2bk_{sr} + ek_1)\theta - (2ac_{sf} + 2bc_{sr} + ec_1)\dot{\theta} - fk_1\varphi - fc_1\dot{\varphi} + F_{fr} + F_{fl} + F_{rl} + F_{rr}$$

$$I_y\ddot{\theta} = ek_1 z_1 + ec_1\dot{z}_1 - (2ak_{sf} - 2bk_{sr} + ek_1)z_s - (2ac_{sf} - 2bc_{sr} + ec_1)\dot{z}_s + ak_{sf}z_{ufl} + ac_{sf}\dot{z}_{ufl} + ak_{sf}z_{ufr} + ac_{sf}\dot{z}_{ufr} - bk_{sr}z_{url} - bc_{sr}\dot{z}_{url} - bk_{sr}z_{urr} - bc_{sr}\dot{z}_{urr} - (e^2k_1 + 2a^2k_{sf} - 2b^2k_{sr})\theta - (e^2c_1 + 2a^2c_{sf} - 2b^2c_{sr})\dot{\theta} - efk_1\varphi - efc_1\dot{\varphi} + aF_{fr} + aF_{fl} - bF_{rl} - bF_{rr}$$

$$I_x\ddot{\varphi} = fk_1 z_1 + fc_1\dot{z}_1 - (fk_1)z_s - (fc_1)\dot{z}_s + ck_{sf}z_{ufl} + cc_{sf}\dot{z}_{ufl} - dk_{sf}z_{ufr} - dc_{sf}\dot{z}_{ufr} + ck_{sr}z_{url} + cc_{sr}\dot{z}_{url} - dk_{sr}z_{urr} - dc_{sr}\dot{z}_{urr} - fek_1\theta - fec_1\dot{\theta} - (f^2k_1 + 2c^2k_{sf} + 2c^2k_{sr})\varphi - (f^2c_1 + 2c^2c_{sf} - 2c^2c_{sr})\dot{\varphi} - dF_{rr} + cF_{fl} + cF_{rl} - dF_{fr}$$

$$m_{ufl}\ddot{z}_{ufl} = k_{sf}z_s + c_{sf}\dot{z}_s - (k_{sf} + k_t)z_{ufl} - c_{sf}\dot{z}_{ufl} + ak_{sf}\theta + ac_{sf}\dot{\theta} + ck_{sf}\varphi + cc_{sf}\dot{\varphi} + k_t z_{fl} - F_{fl}$$

$$m_{url}\ddot{z}_{url} = k_{sr}z_s + c_{sr}\dot{z}_s - (k_{sr} + k_t)z_{url} - c_{sr}\dot{z}_{url} - bk_{sr}\theta - bc_{sr}\dot{\theta} + ck_{sr}\varphi + cc_{sr}\dot{\varphi} + k_t z_{rl} - F_{rl}$$

$$m_{urr}\ddot{z}_{urr} = k_{sr}z_s + c_{sr}\dot{z}_s - (k_{sr} + k_t)z_{urr} - c_{sr}\dot{z}_{urr} - bk_{sr}\theta - bc_{sr}\dot{\theta} - dk_{sr}\varphi - dc_{sr}\dot{\varphi} + k_t z_{rr} - F_{rr}$$

We define state variables as following:

State variables related to vertical motion of the body:

$$x_1 = z_1 \text{ و } x_2 = \dot{z}_1 \text{ و } x_4 = \dot{z}_2 \text{ و } x_5 = z_3 \text{ و } x_6 = \dot{z}_3 \text{ و } x_7 = z_4 \text{ و } x_8 = \dot{z}_4$$

State variables related to vehicle body (sprung mass):

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$x_9 = z_s$ و $x_{10} = \dot{z}_s$ و $x_{11} = \theta$ و $x_{12} = \dot{\theta}$ و $x_{13} = \varphi$ و $x_{14} = \dot{\varphi}$

State variables related to tires (unsprung mass):

$x_{15} = z_{ufl} - z_{fl}$ و $x_{16} = \dot{z}_{ufl}$ و $x_{17} = z_{ufr} - z_{fr}$ و $x_{18} = \dot{z}_{ufr}$

$x_{19} = z_{url} - z_{rl}$ و $x_{20} = \dot{z}_{url}$ و $x_{21} = z_{urr} - z_{rr}$ و $x_{22} = \dot{z}_{urr}$

We note that the number of state variables is twice the degree of freedom. Similar to 1/4 model and simple body model, we can obtain matrices of state space through defining state variables and by placing state matrices in MATLAB software, we can control seven degrees of freedom model and four degrees of freedom body model similar to 1/4 model and simple body model.

DISCUSSION

The aim of designing semi-active suspension system is to decrease vibrations transferred to human body due to the roughness of the road surface and also stability of vehicle that are appeared by keeping contact of the tire with the road. To show the efficiency of the designed controller, we have applied various types of sinusoidal profiles, lump, and real roads that are considered as inputs for the vehicle to the model in this thesis. The results of applying these inputs are given in following. Then, the response of model with seven degrees of freedom and also body model with four degrees of freedom with respect to various types of inputs will be investigated.

Response to lump input:

The considered lump input is like figure 21.

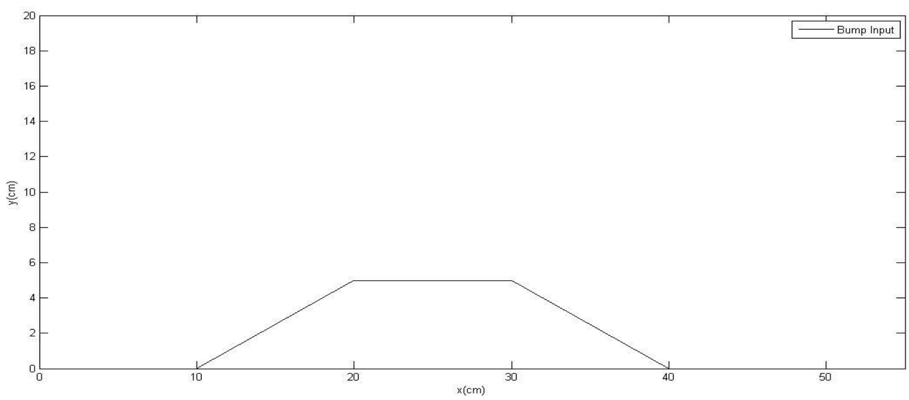

Figure 21-Lump input

Assuming that the vehicle is moving at a speed of 10 m/s, we have presented the tire displacement with respect to the road, the vehicle body acceleration and the human head acceleration in figures 22, 23, and 24.

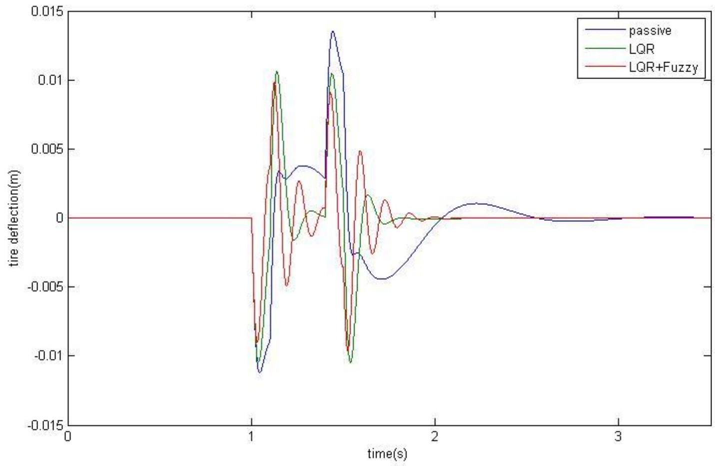

Figure 22- The tire displacement with respect to the road

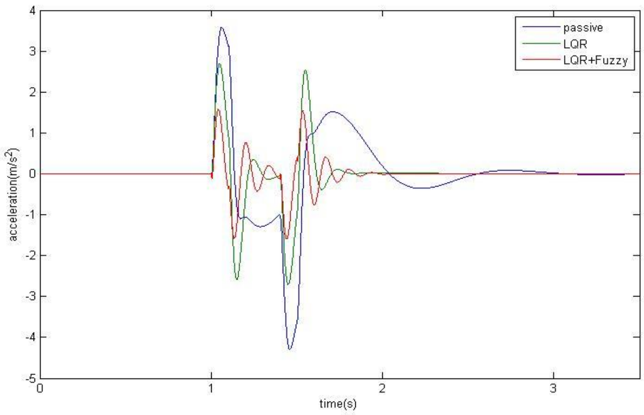

Figure 23- The acceleration of vehicle body

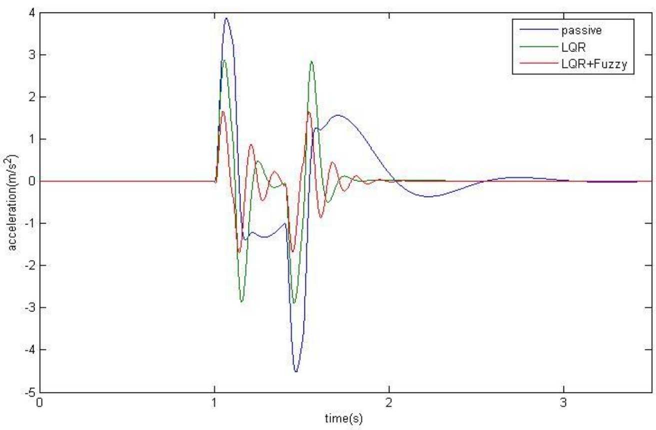

Figure 24- The acceleration of human head

Response to sinusoidal input

Response to sinusoidal input with the frequency of 1 Hz:

Tire displacement with respect to the road, acceleration of vehicle body and human head are given in figures 25, 26, and 27.

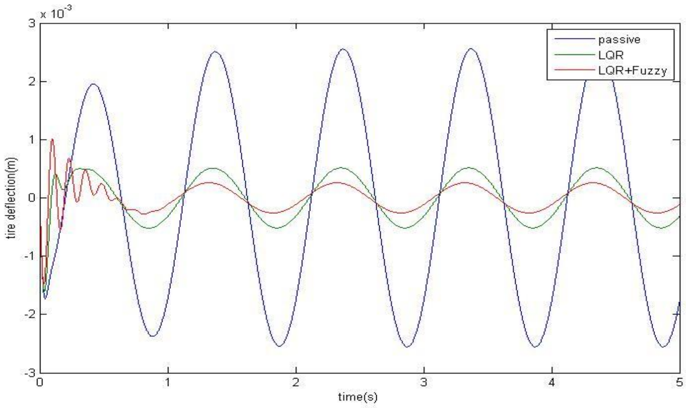

Figure 25- The tire displacement with respect to the road

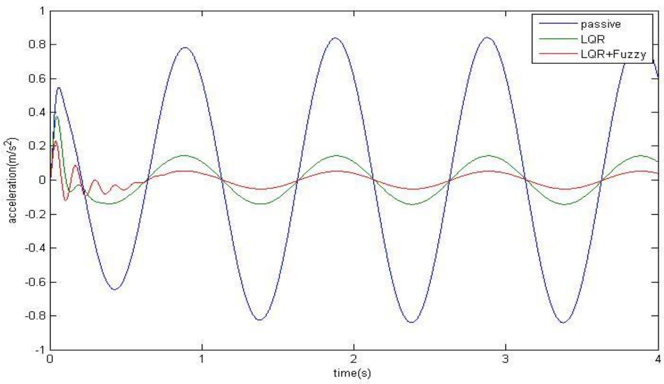

Figure 26- The acceleration of vehicle body

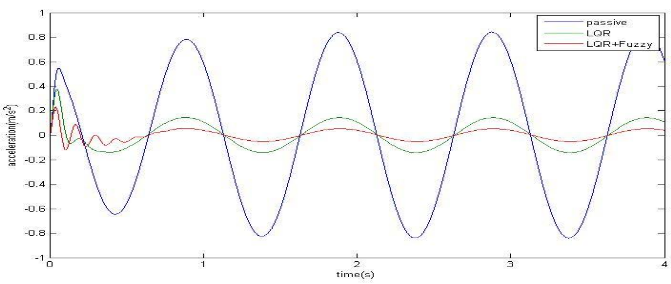

Figure 27- The acceleration of human head

Response to sinusoidal input with the frequency of 10 Hz:

Tire displacement with respect to the road, acceleration of vehicle body and human head are given in figures 28, 29, and 30.

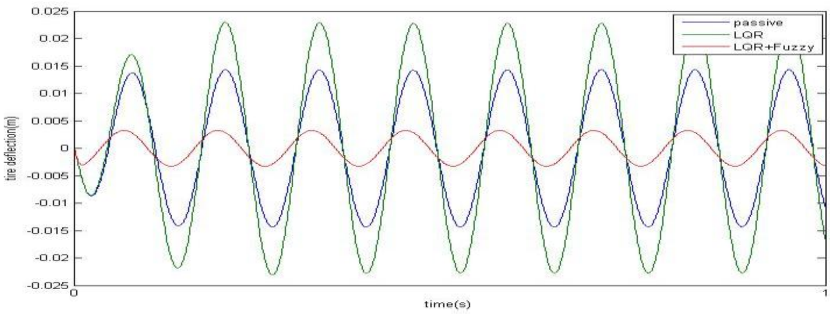

Figure 28- The tire displacement with respect to the road

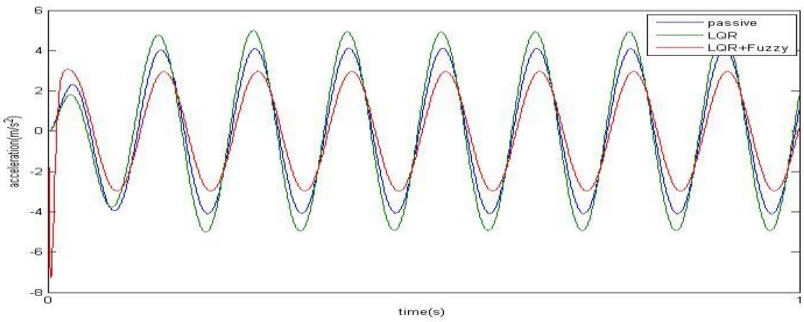

Figure 29- The acceleration of vehicle body

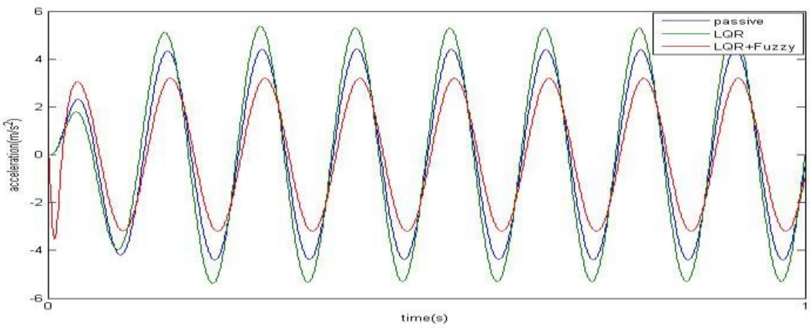

Figure 30- The acceleration of human head

Types of real roads:

Roads are divided into eight types of A to H based on amounts of roughness. In conclusion section, we have used type B, C, and D roads that are of the most common types of the roads. At first, we show fuzzy level for change in amounts of weighting functions in figures 31 and 32.

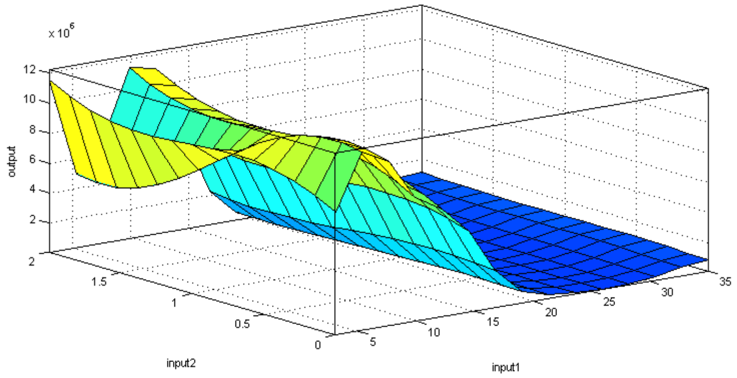

Figure 31- Fuzzy level for weighting function of ride comfort (control of weighting function of acceleration)

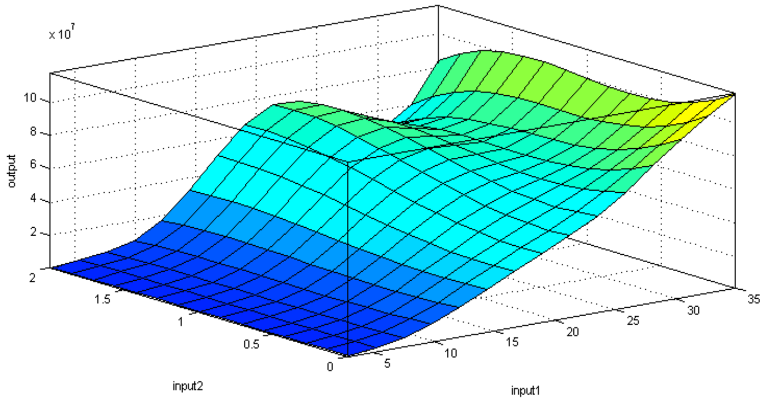

Figure 32- Fuzzy level for stability of weighting function (control of weighting function of tire displacement with respect to road input)

Type B road:

This type of road has a length of 100 m. Vehicle speed on this type of roads has been considered 20 m/s (72 km/h).

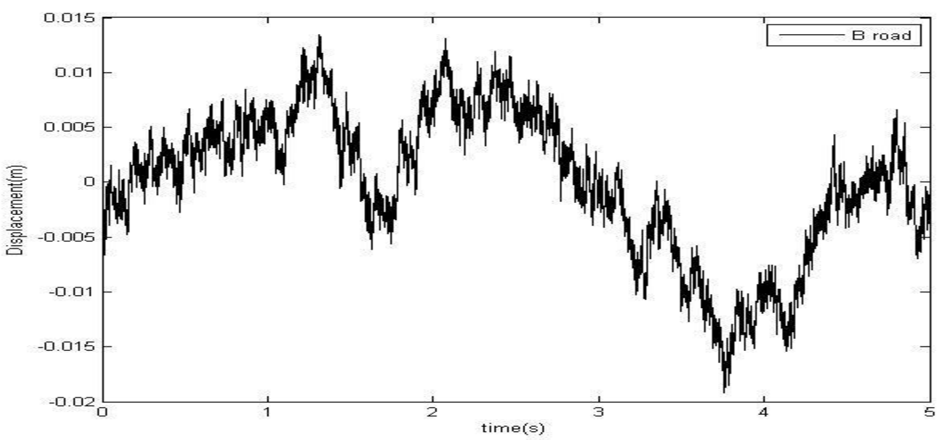

Figure 33- Type B road

We consider trend of variations in vehicle speed on the type B road according to figure 34:

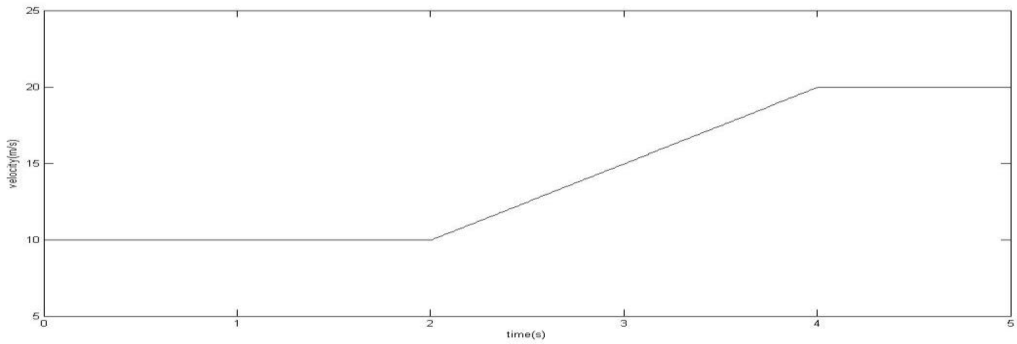

Figure 34- Trend of variations in vehicle speed on the type B road

The weighting function changes related to the tire displacement with respect to the road and the weighting function variations associated with human body acceleration are shown in figures 35 and 36, respectively.

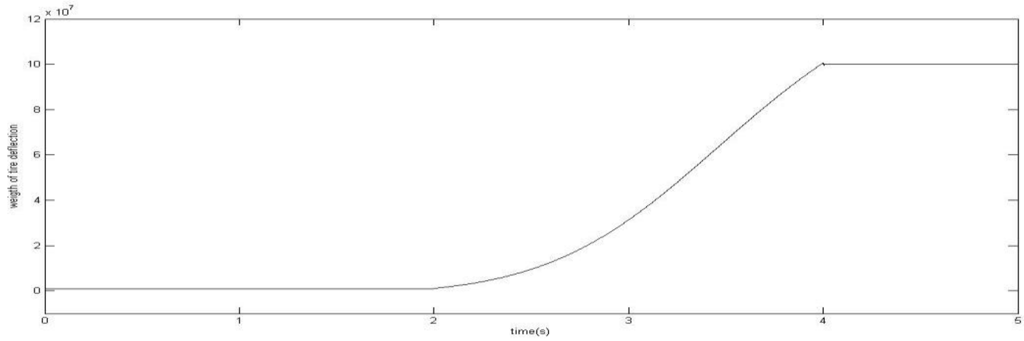

Figure 35- Trend of variations in weighting functions related to tire displacement with respect to the road

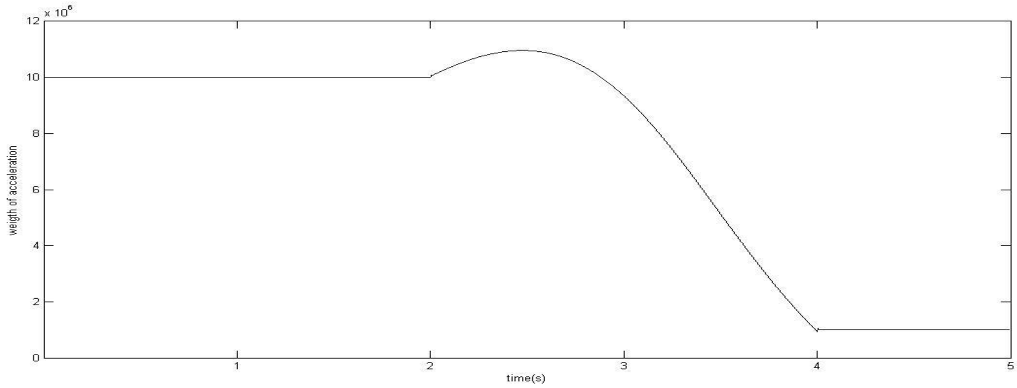

Figure 36- Trend of variations in weighting functions related to human body acceleration

Tire displacement with respect to the road and acceleration of human head are given in figures 37 and 38.

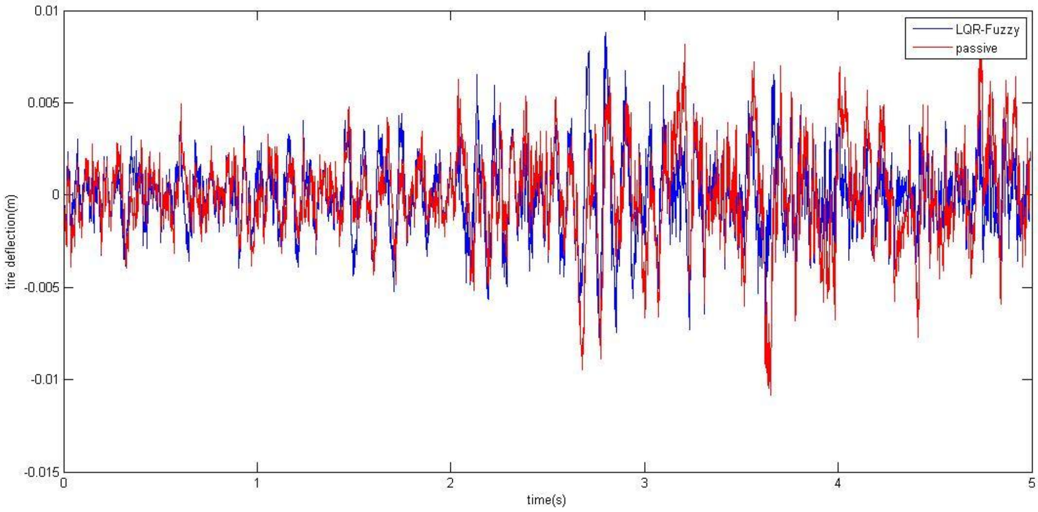

Figure 37- Tire displacement with respect to the road

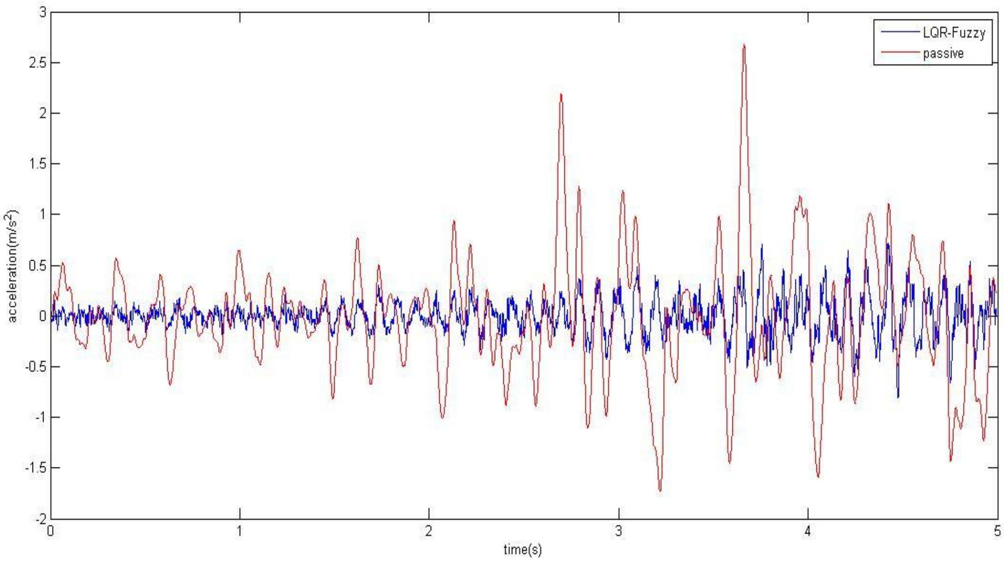

Figure 38- The acceleration of human head

As we can see in the curves, acceleration decreases in lower speeds that are important for our ride comfort and tire displacement with respect to the road has been reduced in higher speeds in which stability is more important to us.

Type C road:

This type of road has a length of 100 m. Vehicle speed on this type of roads has been considered 11 m/s (40 km/h).

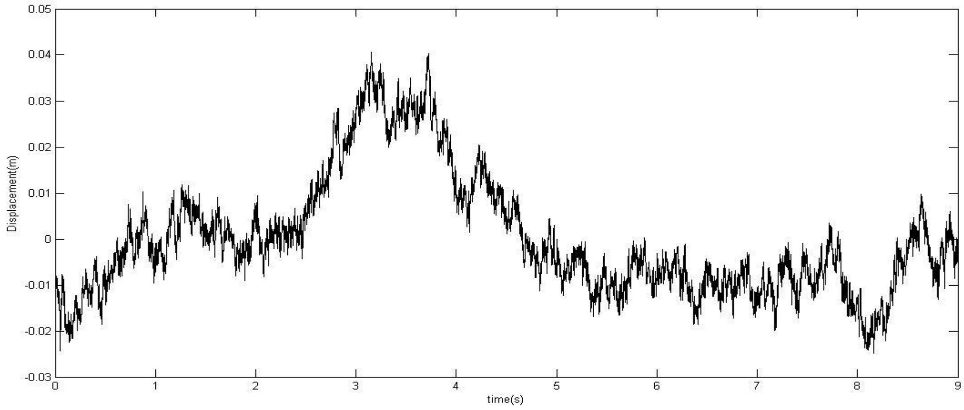

Figure 39- Type C road

We consider trend of variations in vehicle speed on the type C road according to figure 40:

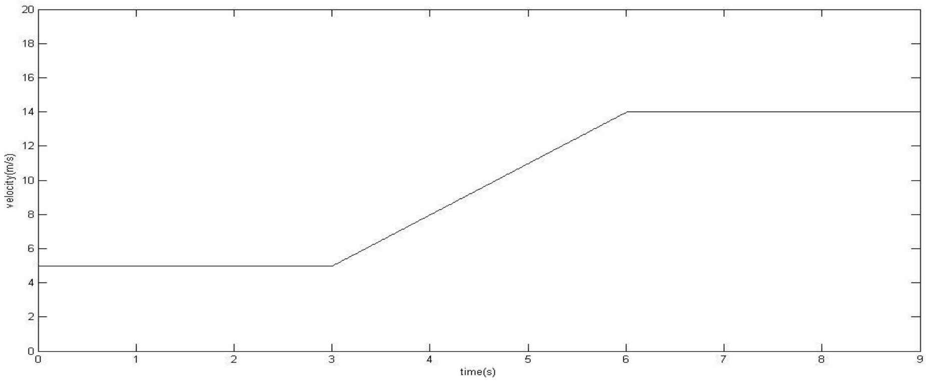

Figure 40- Trend of variations in vehicle speed on the road

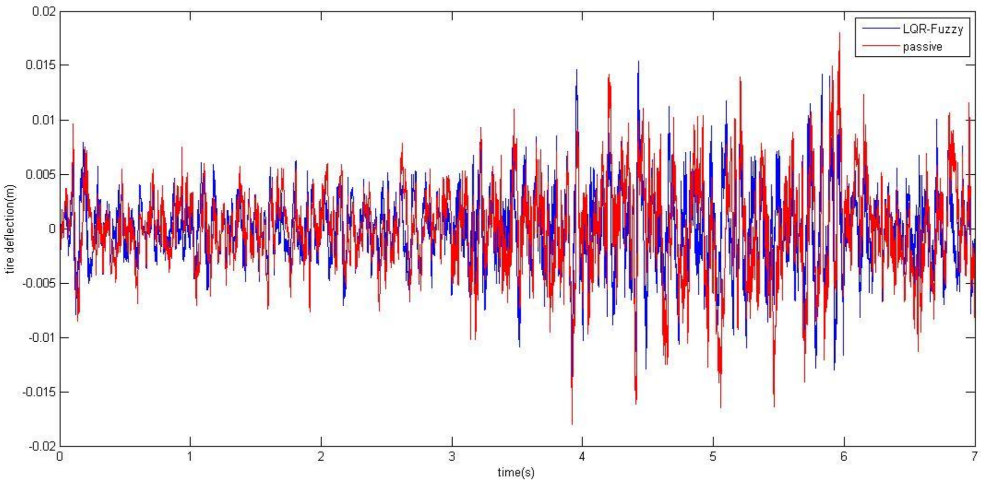

Figure 41- Tire displacement with respect to the road

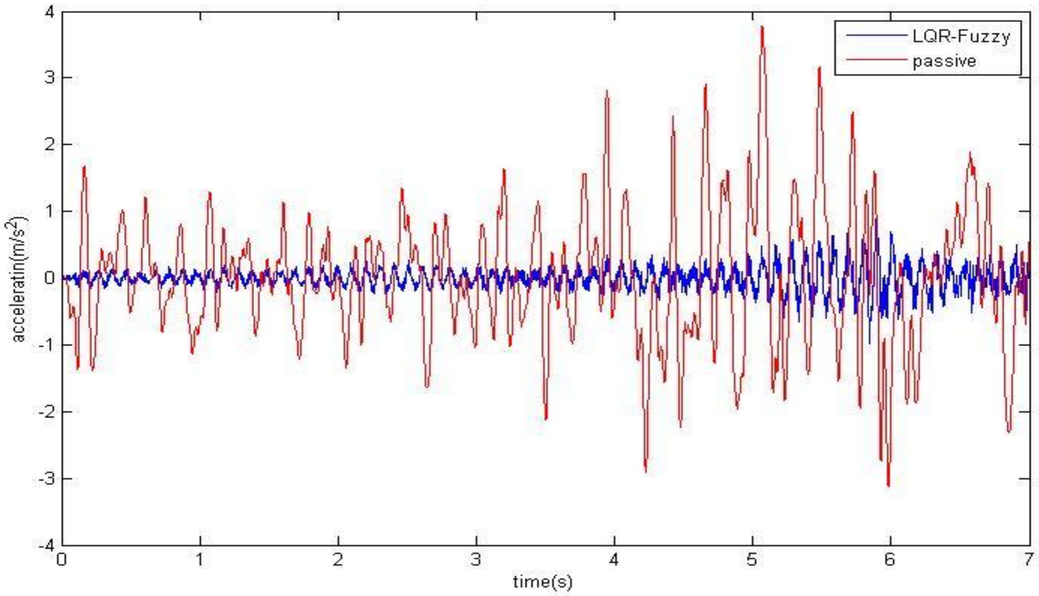

Figure 42- The acceleration of neck and head

Type D road:

This type of road has a length of 100 m and vehicle speed on this type of roads has been considered 5.5 m/s (20 km/h).

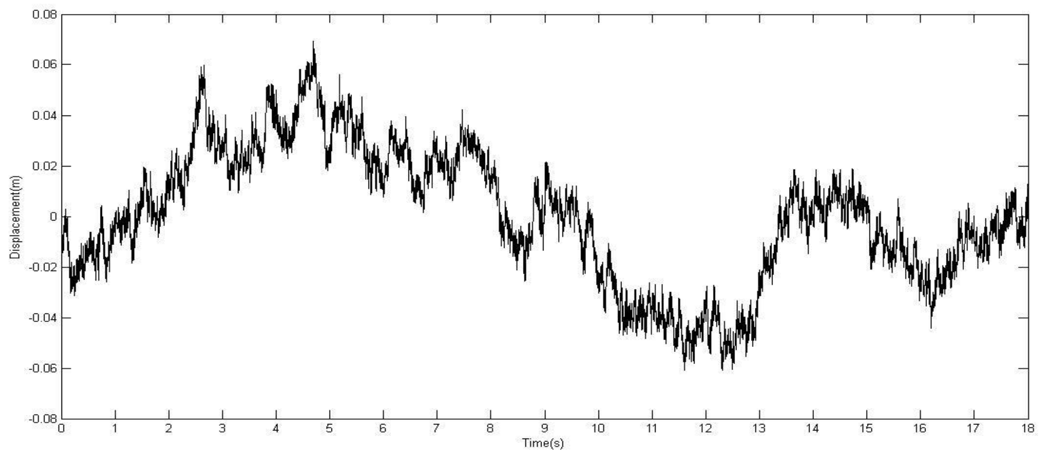

Figure 43- Type D road

We consider trend of variations in vehicle speed on the type D road according to figure 44:

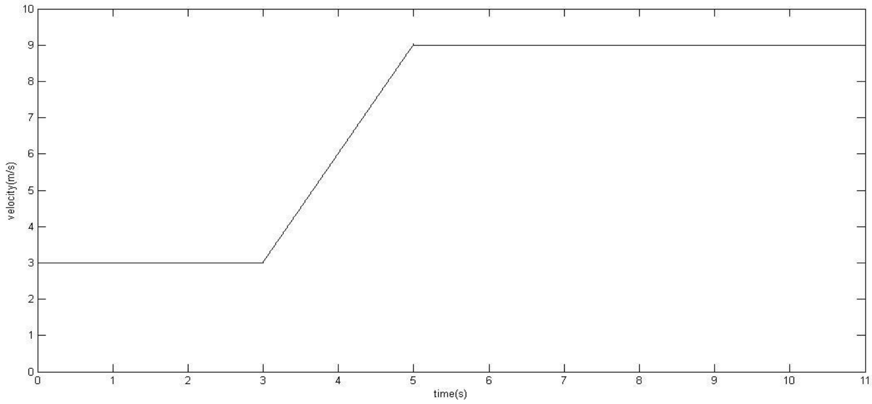

Figure 44- Trend of variations in vehicle speed

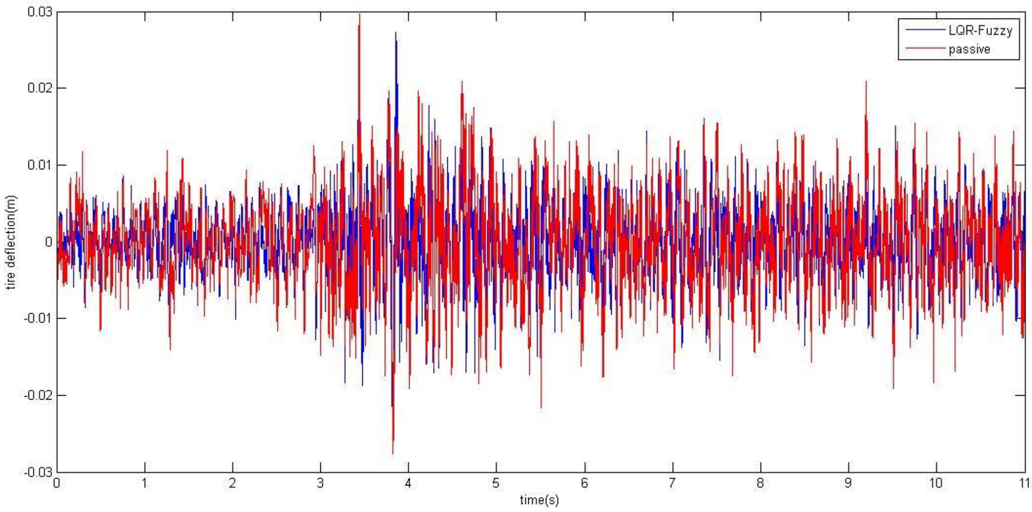

Figure 45- Tire displacement with respect to the road

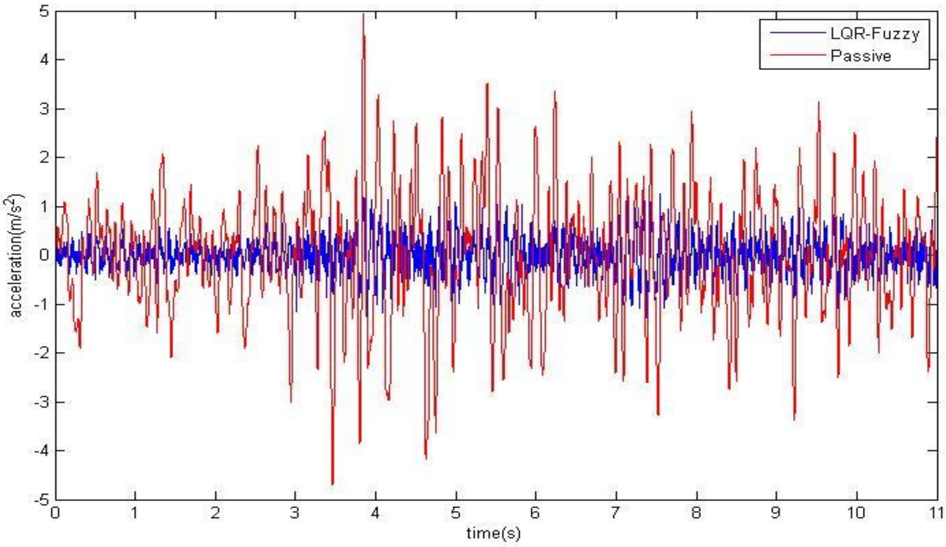

Figure 46- The acceleration of head and neck

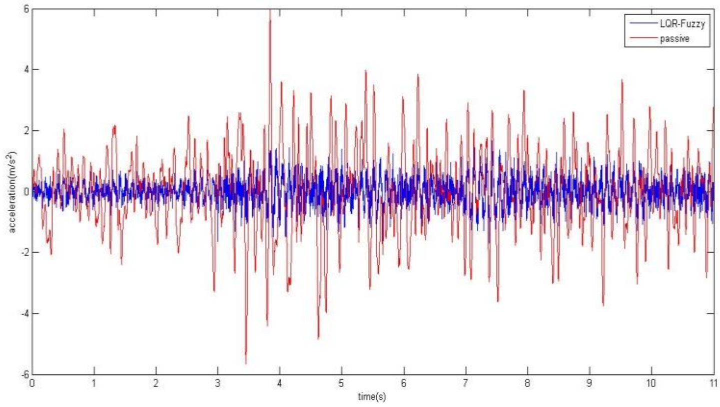

Figure 47- The acceleration of chest, stomach and intestine (viscera)

To be clearer the results obtained from the real road input and the effect of each of controllers, we can use fast Fourier transform (FTT) acceleration curves. As an instance, in this section we show FFT of acceleration of vehicle body and human head caused by type C road input in figures 48 and 49.

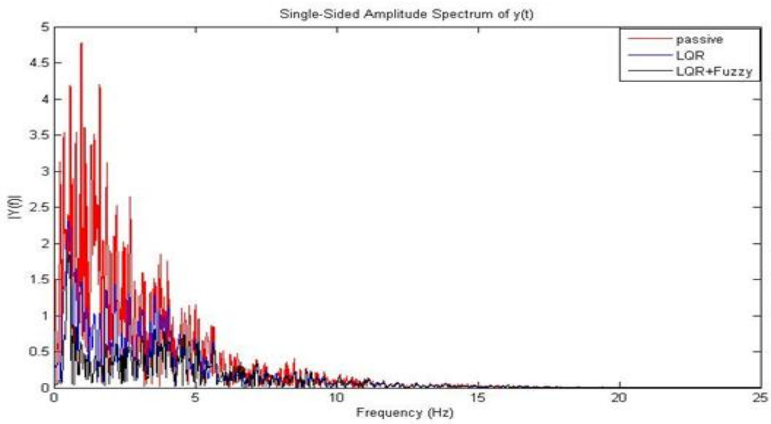

Figure 48- The acceleration of vehicle body

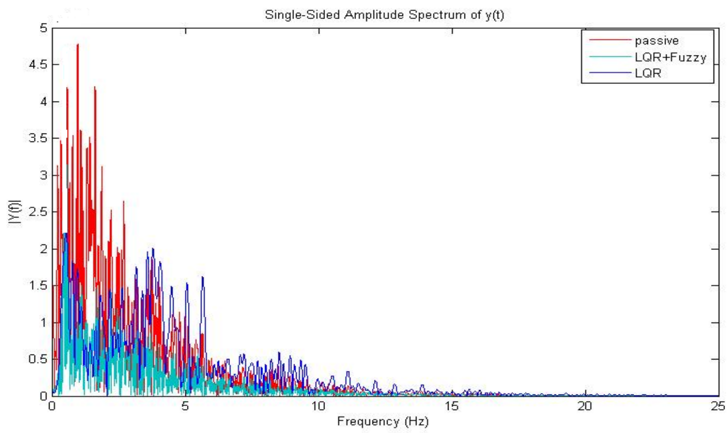

Figure 49- The acceleration of the human head and neck

CONCLUSION

By observing and investigating the results in curves, it is seen that the designed controller in this study greatly decreases accelerations entered to the human body in sensitive frequencies of the body and causes no fatigue for the driver during trip. Also, the occurrence of the vehicle instability in critical situations can be prevented by changing controller weighting functions using fuzzy controller.

SUGGESTIONS

Following suggestions are stated:

1- Considering lateral acceleration as the input of fuzzy controller for determining maneuver state and predicting critical situations.

2- Practical implementation of this study on 1/4 model and the mass that represents one degree freedom model of human body.

3- Using this system for controlling a real vehicle and applying changes in designing the suspension system for embedding the controller.

4- Considering changes of human body model parameters, spring coefficients, and damper used in semi-active suspension system as the input for fuzzy controller to strengthening the system with respect to large changes in system parameters.

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