International Journal of Control and Automation
Vol.7, No.6 (2014), pp.129-142
http://dx.doi.org/10.14257/ijca.2014.7.6.13

Study on Self-tuning Control Strategy of Suspension Systems for Improving Vehicle Ride Performance

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Abstract

In this paper, a new control theory based on fuzzy-logic will be proposed for the purpose of enhancing vehicle ride performance. In the first step, a half car model with four DOF will be analyzed by Lagrange equations after which a conventional semi-active skyhook controller will be built. Then a new control model that considering vehicle mass as well as vehicle speed will be provided, the advantage of this controller will be studied. Harmonic excitation and Random excitation will be given as road input. All the models that proposed will be accomplished through matlab/simulink. The four outcome parameters of two types, namely, the body acceleration and the pitch acceleration will be compared in time domain and frequency domain among three conditions which can be described as passive, conventional skyhook and self-tuning respectively. Finally, the models will be implemented on dsPACE to verify whether the theory can be used on real vehicles. Though the graphics and the hardware in the loop test we can come to a conclusion that vehicle suspensions arm with fuzzy-logic based self-tuning controllers has the best ride properties which hold practical values.

Keywords: *Vehicle suspension, 4DOF model, Fuzzy-logic, Self-tuning, Semi-active, dsPACE, Ride performance*

1. Introduction

The roles of a suspension are support the vehicle chassis, to maintain the force between the tire and the ground. It is known to us that among all the functions that suspension provided, the most impressive one must be isolate the body from road excitations. Important as it is, a great many investigations have been carried out by academics from automobile industries and universities. We all know that active suspension holds the best properties, and lots of academics study about that [1, 4], however, it cost much energy. To compromise the cost and the properties, semi-active suspension which consume little power as well as satisfied ride performance was concerned. To improve the properties of semi-active suspension, a suitable control method is necessary. For a conventional vehicle, semi-active suspension either change the damping coefficient between a few values that preset or change the value continuously by using a MR damper or ER damper [2, 11]. Lots of studies had been investigated in semi-active suspensions, a modified Skyhook Damping Control was proposed by [10], semi-active control on seat systems also taken in [8], a body acceleration based controller was provided in [14], control strategies for semi-active suspension in recent years has been researched and compared in [5]. However, those

ISSN: 2005-4297 IJCA

papers were not involve vehicle parameters change, what we should concern most is to find a way how to get better comfort under different working conditions.

This paper will propose a method for changing the tuning parameters based on varied working conditions using fuzzy logic and a new semi-active control idea, and then compare the result of the three different suspensions. Firstly, dynamic equations of 4DOF model will be derived, after which a self-tuning suspension controller based on fuzzy logic will be run under matlab/simulink, in addition, a test will be carried out in dsPACE to ensure that the policy can be used in a real car. Finally, the frequency spectral density of the three ride parameters will be compared to show the benefits of using the new control method.

2. Half Car Model Analysis

As we will analyze body acceleration and pitch angle acceleration, half car model which is widely used will be proposed in the following. The equations of the system can be derived by Lagrange laws based on Figure 1. The expression of Lagrange laws can be written as follows:

$$\begin{cases} L = T - V \\ \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{q}_j}\right) - \dfrac{\partial L}{\partial \dot{q}_j} + \dfrac{\partial D}{\partial \dot{q}_j} = Q_j \end{cases} \tag{1}$$

Where T represents kinetic energy of the systems, V is the potential energy of the system. D is the dissipated energy in the processing. q_j are the variables of the system and Q_j are external forces. Then the equations of half car system can be derived as follows:

$$\begin{cases} T = \dfrac{1}{2} m_{wf}\, \dot{z}_1^2 + \dfrac{1}{2} m_{wr}\, \dot{z}_3^2 + \dfrac{1}{2} m_{hb}\, \dot{z}_b^2 + \dfrac{1}{2} I_{hp}\, \dot{\theta}_b^2 \\ V = \dfrac{1}{2} k_{sf} (z_2 - z_1)^2 + \dfrac{1}{2} k_{sr} (z_4 - z_3)^2 + \\ \quad \dfrac{1}{2} k_{tf} (z_1 - z_{of})^2 + \dfrac{1}{2} k_{tr} (z_3 - z_{or})^2 \\ D = \dfrac{1}{2} c_{sf} (\dot{z}_2 - \dot{z}_1)^2 + \dfrac{1}{2} c_{sr} (\dot{z}_4 - \dot{z}_3)^2 \\ z_2 = z_b - a\theta_b \\ z_4 = z_b + b\theta_b \\ q_j = [z_1, z_3, z_b, \theta_b]^T \\ Q_{j=}[z_{of} k_{tf}, z_{or} k_{tr}, 0, 0]^T \end{cases} \tag{2}$$

Then the equations can be written into matrix form based on (1) and (2):

$$
\begin{bmatrix} m_{wf} & 0 & 0 & 0 \\ 0 & m_{wr} & 0 & 0 \\ 0 & 0 & m_b & 0 \\ 0 & 0 & 0 & I_{hp} \end{bmatrix}
\begin{bmatrix} \ddot{z}_1 \\ \ddot{z}_3 \\ \ddot{z}_b \\ \ddot{\theta}_b \end{bmatrix}
+
\begin{bmatrix} c_{sf} & 0 & -c_{sf} & ac_{sf} \\ 0 & c_{sr} & -c_{sr} & -bc_{sr} \\ -c_{sf} & -c_{sr} & c_{sf}+c_{sr} & -ac_{sf}+bc_{sr} \\ ac_{sf} & -bc_{sr} & -ac_{sf}+bc_{sr} & a^2c_{sf}+b^2c_{sr} \end{bmatrix}
\begin{bmatrix} \dot{z}_1 \\ \dot{z}_3 \\ \dot{z}_b \\ \dot{\theta}_b \end{bmatrix}
+
$$

$$
\begin{bmatrix} k_{sf}+k_{tf} & 0 & -k_{sf} & ak_{sf} \\ 0 & k_{sr}+k_{tr} & -k_{sr} & -bk_{sr} \\ -k_{sf} & -k_{sr} & k_{sf}+k_{sr} & -ak_{sf}+bk_{sr} \\ ak_{sf} & -bk_{sr} & -ak_{sf}+bk_{sr} & a^2k_{sf}+b^2k_{sr} \end{bmatrix}
\begin{bmatrix} z_1 \\ z_3 \\ z_b \\ \theta_b \end{bmatrix}
=
\begin{bmatrix} z_{of}k_{tf} \\ z_{or}k_{tr} \\ 0 \\ 0 \end{bmatrix}
\tag{3}
$$

Parameters in the formula are as follows. Where z_2 and z_4 are the displacement of the front suspension and the rear suspension respectively, z_1 and z_3 represent displacement of the front suspension and the rear suspension respectively, z_b is the displacement of vehicle center, z_{of} and z_{or} are road inputs, m_{hb} is the vehicle body mass, m_{wf} and m_{wr} are the unspring mass, I_{hp} is the moment inertia, k_{sf} and k_{sr} represent the stiffness of the spring, c_{sf} and c_{sr} are the damper coefficients of the damper, θ_b is the pitch angle, a and b are the distance of the vehicle center to the suspension.

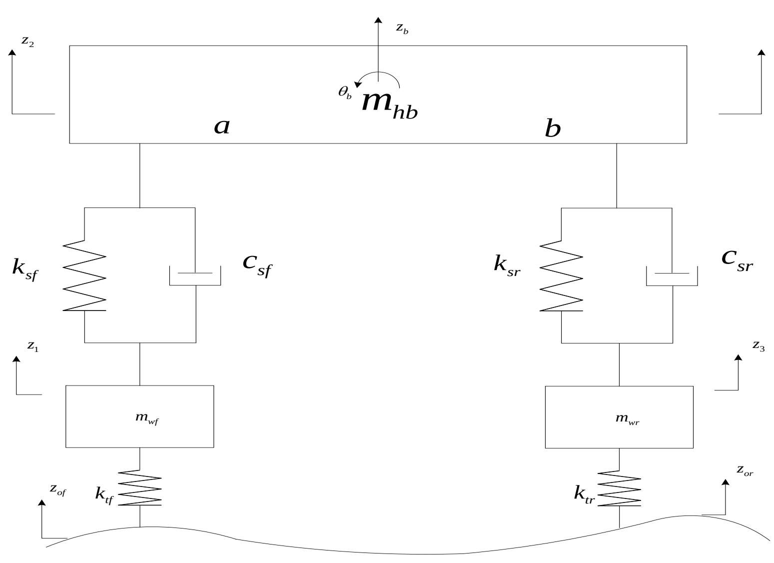

Figure 1. Half Vehicle Model with 4 DPF

3. Conventional Skyhook Control Strategy

A semi-active suspension can be expressed as Figure 2, the damping coefficient is not always constant, which has more than one value. For a conventional semi-active suspension, ride performance always controlled by changing the damper coefficient among numerable values, which usually can be noted as a skyhook gain:

$$c_s = \begin{cases} c_{\max} & if\ \dot{z}_s(\dot{z}_s - \dot{z}_u) \geq 0 \\ c_{\min} & if\ \dot{z}_s(\dot{z}_s - \dot{z}_u) \prec 0 \end{cases} \quad (4)$$

Where $c_{\max}$ and $c_{\min}$ are the maximal value and the minimal value of the damper factor generated by the controlled damper.

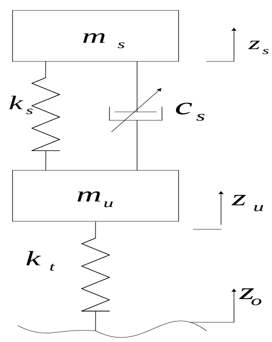

Figure 2. 2DOF Vehicle Model with Semi-active Control

However, the damper factors of this kind of controller cannot always change into the best values that we want to.

4. Fuzzy Logic Based Self-tuning Model

As the damper coefficient above can only have a few constant values, here a new control law where the coefficient is determined by the velocity of spring mass and the relative velocity between spring mass and unspring mass. This kind of damper can be accomplished by using Electrorheological dampers or Magnetorheological dampers whose damper value can change continuously in a very short millisecond. The control equations can be expressed as:

$$c_s = \begin{cases} \alpha(\mathrm{abs}(K\dot{z}_s(\dot{z}_s - \dot{z}_u)))_{sat[\mathrm{cmax,\ cmin}]} & if\ \dot{z}_s(\dot{z}_s - \dot{z}_u) \geq 0 \\ \alpha c_{\min} & if\ \dot{z}_s(\dot{z}_s - \dot{z}_u) \prec 0 \end{cases} \quad (5)$$

Where K is spring stiffness and $\alpha \in [1, 1.4]$ is tuning parameters whose value is decided by the mass and the speed of vehicles. The damping factor of the systems can be written: $\varsigma = \frac{c_s}{2\sqrt{Km_{mb}}}$.When the mass changed the factor will follow, in addition, the road input always decided by the speed of the car when driving. So a better law can keep a balance among different conditions though changing the value of c_s.

As the mass of the vehicle and the speed change randomly, the best way to solve this is using a fuzzy logic law, the scheme of this law can be expressed as Figure 4.

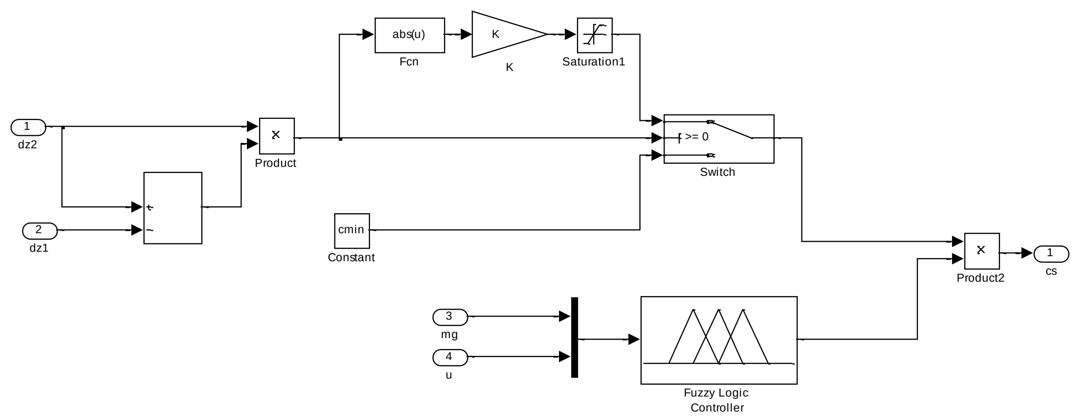

Figure 4. Fuzzy Logic Scheme of I/O Parameters

As we can see from the scheme, the output tuning parameter "a" is controlled to maintain a good ride comfort by m_i and u which stand for mass increase and vehicle speed respectively. Then set m_{gain} and u as input language, fuzzy subset for m_i and u, set to be [ZO, PS, PM, PB, PL] ,whose discourse is [0,200] and [0,130] respectively. While fuzzy subset for output "a", set to be [ZO, PS, PM, PB, PL], whose discourse is [1,1.4].Then a fuzzy logic rule table can be generated base on the scheme as the following table.

Table 1. Fuzzy Logic Relationships among there Parameters

m_i \ u (a)	ZO	PS	PM	PB	PL
ZO	ZO	PS	PS	PM	PB
PS	PS	PS	PM	PB	PB
PM	PS	PM	PM	PB	PL
PB	PM	PB	PB	PB	PL
PL	PB	PB	PL	PL	PL

The form of rules is "if a and b then c", Here we choose trim form membership function, and adjust the amount of it, then rename relative variable and put it into the rule table, after which use Mamdani reasoning method as the way of solving the defuzzification. Then the fuzzy logic table can be listed as Table 1, while relationships of the parameters are as Figure 5 and Figure 6.

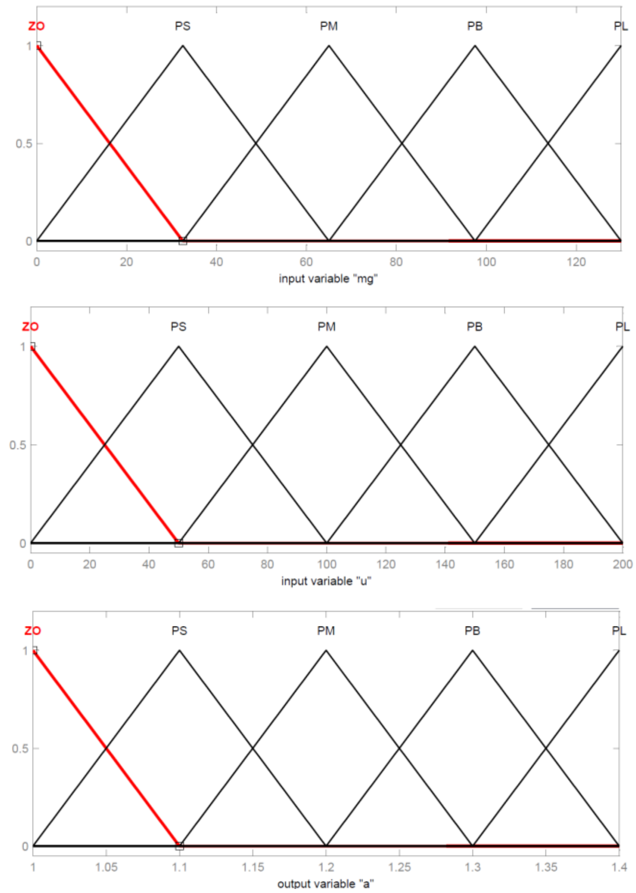

Figure 5. Membership Functions of Fuzzy Logic Controller Parameters

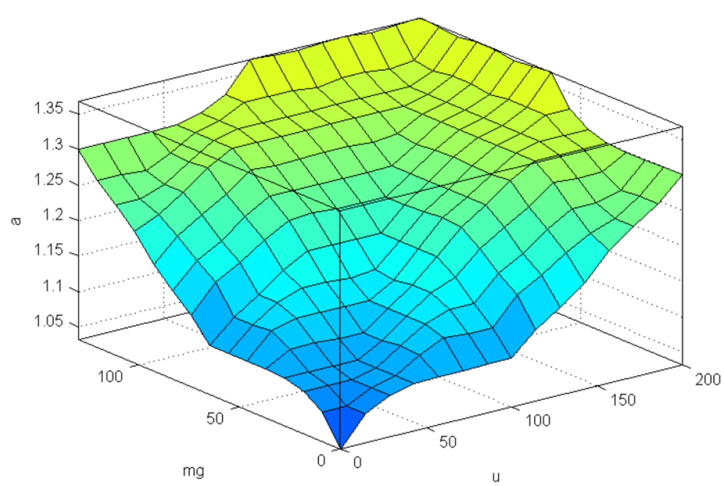

Figure 6. Relations Surfaces Curve between Inputs and Out put

5. Road Input Model

Analysis in time domain and frequency domain will be studied after the models are confirmed. Here the sinusoidal harmonic will be chosen to be the excitation in time domain whose expression is: $z_o = A\sin\omega t$ .Where A=0.02m, ω=5.

However, a random road with C level will be built as a extinction which can simulate real work conditions. Recently, the methods of building a random road surface input can be described as linear filtering methods and harmonic superposition method. Here we use the previous thanks to its simplicity and accuracy. The main idea of this way is to get values obtained filter by calculating and processing the power spectrum on the road, after which the computer-generated normal random number road waveform is obtained by the filter. The equation is as follows:

$$\dot{y}(t) = -2\pi f_0 y(t) + 2\pi n_0 \sqrt{G_q(n_0)u}\, w(t) \quad (6)$$

Then the differential equation will be built in matlab/simulink as follows:

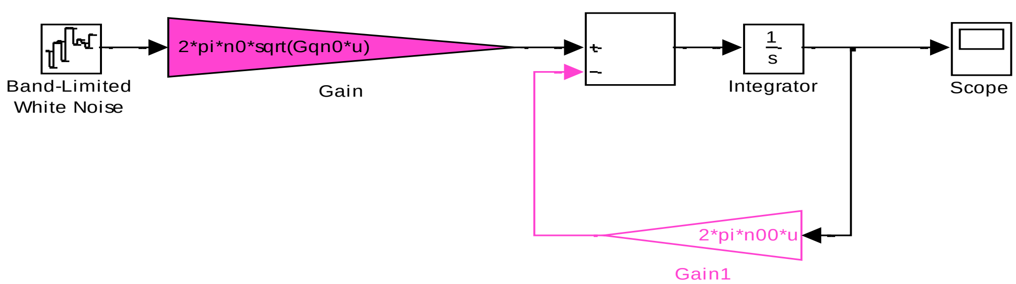

Figure 7. Road Input in Matlab/Simulink

where f_0 =0.011Hz stands for Offline cutoff frequency, $y(t)$ is road roughness amplitude, $w(t)$ is a white noise whose intensity is 1, u is vehicle speed , n_0 is frequency of reference Space whose value is 0.1HZ, $G_q(n_0)$ is road roughness coefficient ,which is a constant decided by road conditions. For road of C level, $G_q(n_0) = 256\times10^{-6} m^3$ .The road input at 20m/s is as the following Figure 8.

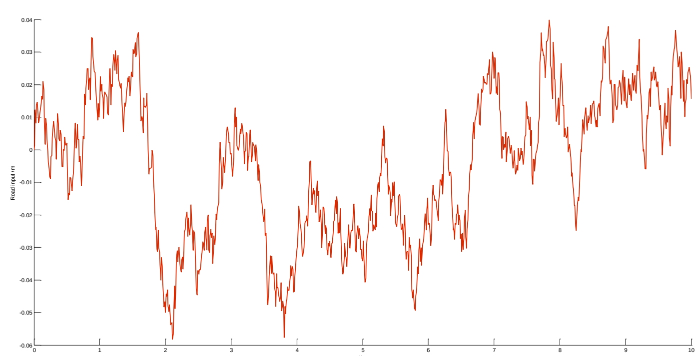

Figure 8. Input Extinction under C Level Road

6. Simulation and HIL Experiment

The simulation model in matlab/simulink can be built as Figure, parameters of the vehicle model can be seen in Table 2.

After finish building the model in simulink circumstance, the model will generated C code into dsPACE microAutobox to carry the HIL test, by which we can use the theory in a real car.

Table 2. Parameters of Vehicle

parameters	value	parameters	value
m_{hb}	690kg	k_{sf}	17000N/m
m_{wf}	40.5kg	k_{sr}	22000N/m
m_{wr}	45.4kg	k_{tf}	192000N/m
I_{hp}	1222kg.m^2	k_{tr}	192000N/m
a	1.25m	c_{sf}	1500N/m/s
b	1.51m	c_{sr}	1500N/m/s

Figure 9. HIL Test in ds PACE Micro Autobox

Set c_{max}=2500 N/m/s and c_{min}=1000N/m/s, simulation time is set to be 10 seconds. Then the simulation results can be got when the input is sinusoidal harmonic as follows:

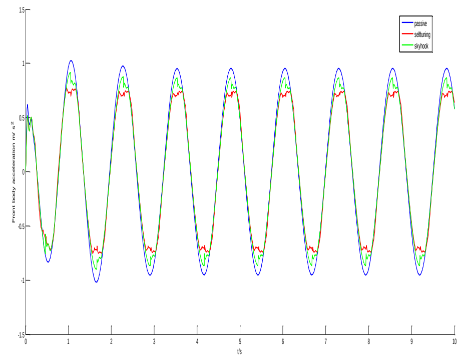

Figure 10. Front Body Acceleration

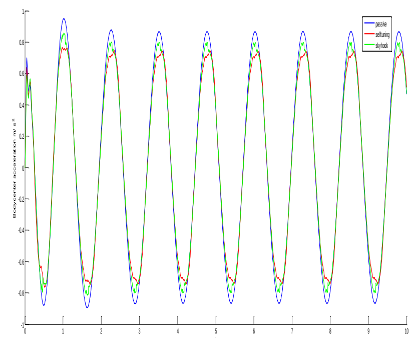

Figure 11. Body Center Acceleration

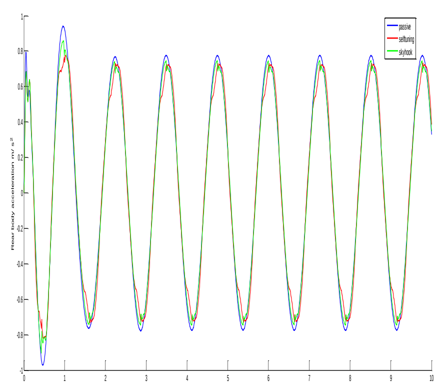

Figure 12. Rear Body Acceleration

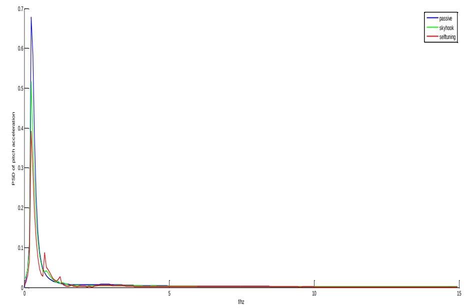

Figure 13. PSD Analysis of Pitch Acceleration

The spectrum density analysis of the results under C level road can listed as following Figures when m_{hb} is 690kg and 890kg respectively and the speed of the vehicle is 10m/s and 20m/s respectively.

Then results under 10m/s and 690kg are listed:

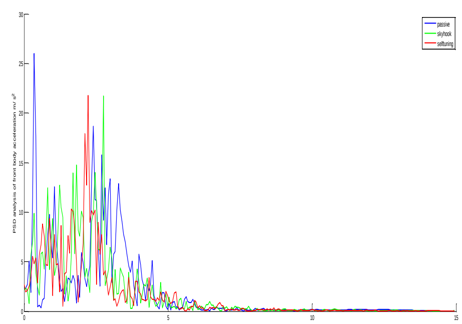

Figure 14. PSD Analysis of Front Body Acceleration under 10m/s

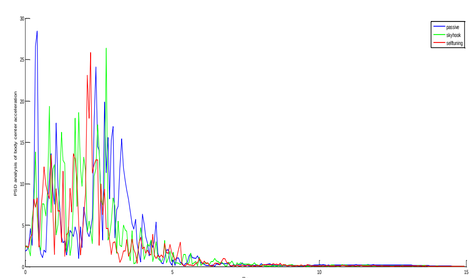

Figure 15. PSD Analysis of Body Center Acceleration under 10m/s

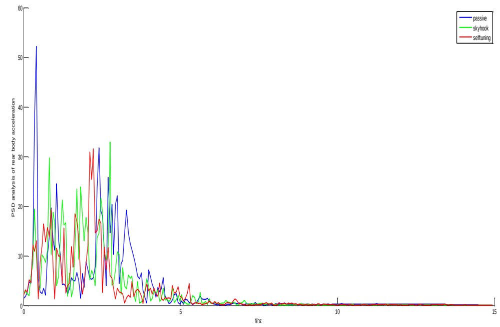

Figure 16. PSD Analysis of Rear Body Acceleration under 10m/s

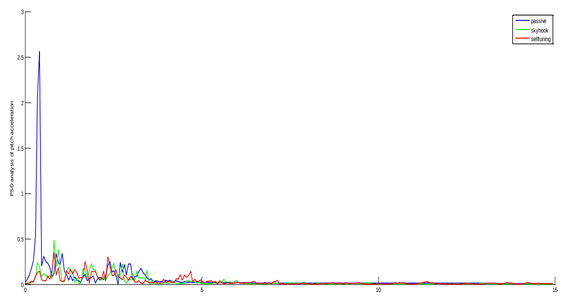

Figure 17. PSD Analysis of Pitch Acceleration under 10m/s

Results under 890kg and 20m/s are listed:

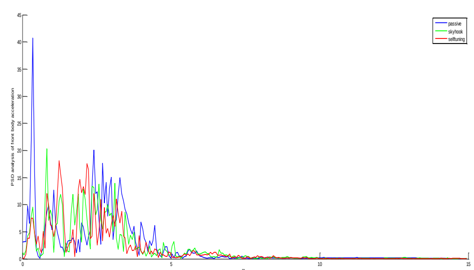

Figure 18. PSD analysis of front body acceleration under 20m/s

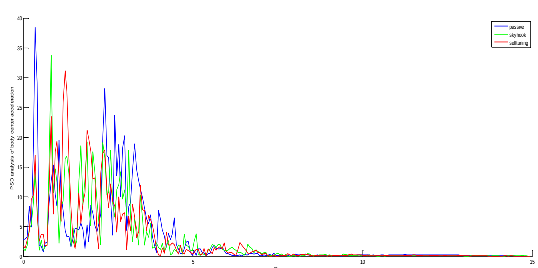

Figure 19. PSD analysis of body center acceleration under 20m/s

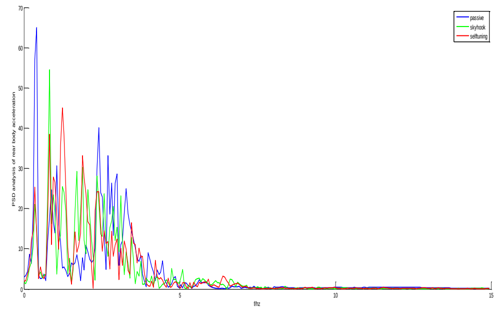

Figure 20. PSD Analysis of Rear Body Acceleration under 20m/s

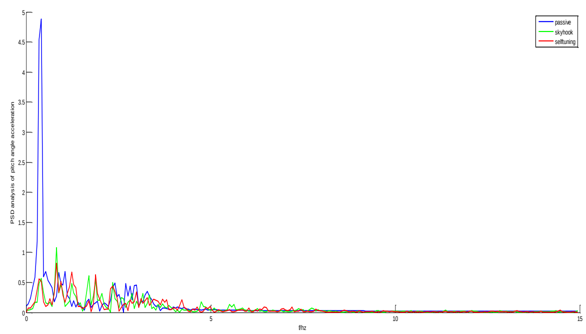

Figure 21. PSD Analysis of Pitch Acceleration under 20m/s

As seen from the Figures above among the three conditions, the fuzzy logic one rank the best in controlling the parameters increase.

7. Conclusion

In this paper, half car model with 4 DOF is built, the dynamics differential equations then be deduced by using Lagrange laws. A new control model based on fuzzy logic and conventional skyhook method has been derived. Ride performance parameters among three kinds of controller are compared by simulation in matlab/simulink and HIL test that carried by dsPACE, from which we can come into the conclusions that vehicle suspension systems arm with the new controller have more advantages than conventional skyhook one and the passive one in improving ride performance though the analysis in the time domain and the frequency domain for the reason that the proposed controller can adapt to different working conditions which other controller cannot finish. In addition, the new theory can be confirmed to use in a real car though the HIL test by dsPACE, which verify that the self-tuning one has application values.

Acknowledgements

This work is supported by the International cooperation projects (No. 2010DFB83650) and Horizontal projects (No. 2012220101001314).

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