# ENHANCING TRAVEL COMFORT OF QUARTER CAR WITH DRIVER MODEL USING FRACTIONAL ORDER TERMINAL SLIDING MODE CONTROLLER WITH DUAL ACTUATOR

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***Abstract:*** *The ride quality and travel comfort of the passenger is based on the type of the suspension system used in the vehicle. The active suspension system is one of the good choice to reduce the vibration and enhance the travel comfort. In this paper, a quarter car with driver model and dual actuator is considered for analysis. To reduce the vibration and increase the travel comfort, different types of Sliding Mode Controllers (SMC) such as Terminal SMC (TSMC), Fractional Order SMC (FOSMC) and Fractional order Fuzzy SMC (FOTSMC) are designed and simulated in the active suspension system of the quarter car with driver model. Different kinds of road disturbances are given to the system to stimulate the vibration in the system. The responses of the controllers with the quarter car system is compared with the passive system. The results shows that the FOTSMC performs better than TSMC and FOSMC.*

***Key words:*** *Actuators, Fractional Order Terminal Sliding Mode Controller, Sliding mode control, Vibration control.*

## 1. Introduction

Suspension system in a vehicle is used to enhance the travel comfort and ride quality. In the vehicle suspension system passive, semi active and active suspension are the three types used to reduce the vibration. Different kinds of springs are used in passive suspension system. In semi active suspension the spring and damper parameters are changed with respect to the road condition during the run time. Hence vibration reduces to a particular level and it requires minimum power to perform. In case of Active Suspension System (ASS) an external control force is applied to the opposite direction of the vibration. Therefore it reduces the vibration better than semi active and passive suspension systems. The active and semi active suspension systems are used in addition to the passive suspension system in the vehicles.

While travelling in a car, comfort of the passenger will be more when there is a minimum vibration. Since the road surfaces are not smooth, the vehicle experience the vibrations. These vibrations affects the health of the passengers and the life of the vehicle. The wear and tear of the vehicle will also increase. Therefore the ASS is designed to handle these vibrations. Different kinds of algorithms are used to produce the control force in the ASS. The control force should be as minimum as possible and should change rapidly with respect to the changes in the road disturbances.

Considering the one fourth of the vehicle for the analysis of the vibration control is a common practice among the researchers [1 &2]. These type of quarter car model has two masses namely sprung mass and unsprung mass [3]. On top of the sprung mass an integrated Seat suspension [4] with Chassis suspension and Driver body model (SCD) have been considered for vibration control in [5]. The driver body model can be considered either as a single mass [5] or four masses as discussed in [6 &7]. The concept of active seat suspension which acting as a secondary controller is discussed in [7] along with the main car suspension is available. The control strategies for the quarter car is reviewed in [8].

The control strategies for the quarter car with driver model are discussed in the following papers. A semi-active suspension controller using Sliding Mode Control (SMC) for SCD [9], design of the optimal seat suspension using Genetic algorithm [10], state feedback and static output feedback controllers [7] are designed for an 8 Degree Of Freedom (DOF) quarter car model. The driver's bio mechanical effects [11] are considered for analysis of vibration control. As for as the SMC is concern, Grey Fuzzy SMC [12], type-2 FLC based SMC [13], Robust Fuzzy based SMC [14], model-free adaptive SMC [15] are designed to enhance the performance of the quarter car model. In [16] SMC is used to estimate the car body mass of the quarter car. Fractional Order SMC (FOSMC) [17-20] and Terminal SMC (TSMC) [21 -23] are used in various applications to improve the performances of the system. Fractional Order Terminal SMC (FOTSMC) is designed for a dynamical systems with uncertainty in [24].

In this paper, FOTSMC is proposed to enhance the travel comfort of the Quarter Car with integrated Seat suspension and Driver model (QCSD) with Dual Actuator (DA). The performances of the controller is compared with FOSMC, TSMC and the passive suspension system. Three types of road profiles are considered to test the performance of the controller. This paper is organized as follows. In Section 2, Quarter car model is discussed. In Section 3, controllers design approaches for the proposed model is presented. In section 4, the numerical simulation are discussed. Finally, results and conclusions are summarized in Section 5.

## 2. Quarter car with Driver Model

The QCSD has 8 DOF. In general a quarter car model has 2 DOF with its sprung mass ($m_s$) and unsprung mass ($m_u$). It is described by Equation (1.1) and (1.2), along with this an integrated seat suspension components includes another 2 DOF (Equation (1.3) and (1.4)) and a driver human body model adds another 4 DOF Equation (2.1) to (1.8). The QCSD is shown in Figure 1. The dynamic vertical motion Equations for the QCSD with Single Actuator (SA) are as follows.

$$m_u\ddot{y}_u = -k_t(y_u-y_r) - c_t(\dot{y}_u-\dot{y}_r) + k_s(y_s-y_u) + c_s(\dot{y}_s-\dot{y}_u) - f_a \quad (1.1)$$

$$m_s\ddot{y}_s = -k_s(y_s-y_u) - c_s(\dot{y}_s-\dot{y}_u) + k_{ss}(y_f-y_s) + c_{ss}(\dot{y}_f-\dot{y}_s) + f_a \quad (1.2)$$

$$m_f\ddot{y}_f = -k_{ss}(y_f-y_s) - c_{ss}(\dot{y}_f-\dot{y}_s) + k_c(y_c-y_f) + c_c(\dot{y}_c-\dot{y}_f) \quad (1.3)$$

$$m_c\ddot{y}_c = -k_c(y_c-y_f) - c_c(\dot{y}_c-\dot{y}_f) + k_1(y_1-y_c) + c_1(\dot{y}_1-\dot{y}_c) \quad (1.4)$$

$$m_1\ddot{y}_1 = -k_1(y_1-y_c) - c_1(\dot{y}_1-\dot{y}_c) + k_2(y_2-y_1) + c_2(\dot{y}_2-\dot{y}_1) \quad (1.5)$$

$$m_2\ddot{y}_2 = -k_2(y_2-y_1) - c_2(\dot{y}_2-\dot{y}_1) + k_3(y_3-y_2) + c_3(\dot{y}_3-\dot{y}_2) \quad (1.6)$$

$$m_3\ddot{y}_3 = -k_3(y_3-y_2) - c_3(\dot{y}_3-\dot{y}_2) + k_4(y_4-y_3) + c_4(\dot{y}_4-\dot{y}_3) \quad (1.7)$$

$$m_4\ddot{y}_4 = -k_4(y_4-y_3) - c_4(\dot{y}_4-\dot{y}_3) \quad (1.8)$$

This QCSD has dual actuators. The first actuator is mounted in between the sprung mass and unsprung mass. This actuator with the suspension system is called as the car suspension. The second is mounted in between the

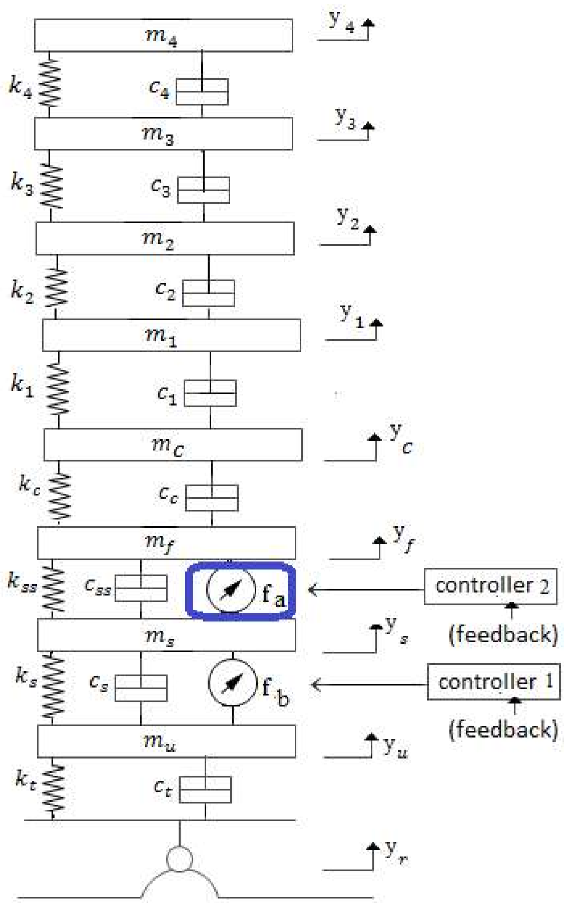


Figure 1 Quarter Car with integrated Seat suspension and Driver model (QCSD)

sprung mass and the frame. This actuator with the suspension system is called as the seat suspension. A linear electromagnetic actuator can be used to produce the control force. Since the performance of the QCSD with SA is compared against QCSD with DA, the controllers for the QCSD with DA is designed based on the modified Equations. In the presence of the seat suspension system Equation (2.2) and (2.3) will be modified as follows

$$m_s\ddot{y}_s = -k_s(y_s - y_u) - c_s(\dot{y}_s - \dot{y}_u) + k_{ss}(y_f - y_s) + c_{ss}(\dot{y}_f - \dot{y}_s) + f_a - f_b \quad (2.9)$$

$$m_f\ddot{y}_f = -k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) + k_c(y_c - y_f) + c_c(\dot{y}_c - \dot{y}_f) + f_b \quad (2.10)$$

where
$m$ - mass,
y - displacement,
$c$- damping constants,
k- the spring constant
$y_r$ -the road displacement input.
$f_a$ -actuator force by the car suspension.
$f_b$ -actuator force by the seat suspension.

The subscripts t, s, ss, u, f and c are representing tyre, sprung, seat suspension, unsprung, frame and cushion of seat. The driver mass consists of four parts such as thighs, lower torso, upper torso and head, the same are represented in subscripts from 1 to 4 respectively

## 3. Design of controllers

### *3.1Design of Fractional order Sliding Mode Controller*

To control the vibration in the vehicle, SMC is one of the good choice because of the uncertainties in the road disturbance and it is also one of the simple and effective robust control. SMC produces the control signal [25 &26] which includes the principles of inverse control law and an additional terms to deal with model uncertainty. In SMC, the model uncertainty is dealt in terms of updating the model during operation with respect to measured performances

$$ {}_aD_t^{\alpha} = \begin{cases} \dfrac{d^{\alpha}}{dt^{\alpha}} ------\rightarrow \alpha > 0 \\ 1 ---------\rightarrow \alpha = 0 \\ \int_a^t (d\tau)^{-\alpha} -----\rightarrow \alpha < 0 \end{cases} \quad (2.1)$$

Fractional calculus is extension of the integer order calculus into non integer order calculus [27]. The basis operation of the fractional calculus is defined as

where a and t are the upper and lower limit of the fractional operation, $\alpha$ is the order of the fractional operation. The commonly used definition is Caputo fractional calculus, which is defined as

$${}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(n-\alpha)} \int_{\alpha}^{t} \frac{f^{(n)}(\tau)}{(t-\tau)^{\alpha-n+1}} d\tau \quad (2.2)$$

where m-1 < $\alpha$ < m, m < N, from the above definition the fractional calculus has higher degrees of freedom. In order to design the SMC, the required Lyapunov's function is considered as V = ½ $s^2$. The existence condition for sliding mode is possible when

$$\dot{V} = s\dot{s} < 0 \quad (2.3)$$

where s is the sliding surface

To design the FOSMC the state variables $x_1$ and $x_2$ for the QCSD with SA is chosen as follows

Suspension deflection is $x_1 = y_s - y_u$ (2.4)

Car body velocity is $x_2 = \dot{y}_s$ (2.5)

The necessary condition [25] to drive the state trajectory toward the sliding surface is

$$\dot{s}(x,t) = 0 \quad (2.6)$$

The fractional order sliding surface is,

$$s = D^{\alpha} x_1 + c x_1 \quad (2.7)$$

where c is a sliding surface gain,taking derivative on both sides

$$\dot{s} = D^{\alpha-1}\dot{x}_2 + c\dot{x}_1 \quad (2.8)$$

By substituting the state variables and simplification, the equivalent control force is

$$f_{a\_equ} = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s D^{1-\alpha}(\dot{y}_s - \dot{y}_u) \quad (2.9)$$

Hence the desired control force is,

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s D^{1-\alpha}(\dot{y}_s - \dot{y}_u) - k_1 m_s sign(s) \quad (2.10)$$

where $k_1 m_s$ sign(s) is the switching control, which satisfies the desired criteria as per the Equation (2.3) and brings the system in to the sliding surface and converges to zero in finite time. $k_1$= n+$f_1$ and n is a positive constant

$$f_1 = -\frac{k_s}{m_s}(y_s - y_u) - \frac{c_s}{m_s}(\dot{y}_s - \dot{y}_u) + \frac{k_{ss}}{m_s}(y_f - y_s) + \frac{c_{ss}}{m_s}(\dot{y}_f - \dot{y}_s) \quad (2.11)$$

In case of the QCSD with DA the Equation(2.10) is modified as

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) + f_b - cm_s D^{1-\alpha}(\dot{y}_s - \dot{y}_u) - k_1 m_s sign(s) \quad (2.12)$$

To design the integrated seat suspension active force $f_b$, the state variables are as follows.

$$x_1 = y_f - y_s \quad (2.13) \text{ and } x_2 = \dot{y}_f \quad (2.14)$$

the sliding surface is chosen as per the Equation (2.7). By substituting the state variables and simplification, the equivalent control force is

$$f_{b\_equ} = k_s(y_f - y_s) + c_s(\dot{y}_f - \dot{y}_s) - k_{ss}(y_c - y_f) - c_{ss}(\dot{y}_c - \dot{y}_f) - cm_f D^{1-\alpha}(\dot{y}_f - \dot{y}_s) \quad (2.15)$$

Hence the desired control force is

$$f_b = k_s(y_f - y_s) + c_s(\dot{y}_f - \dot{y}_s) - k_{ss}(y_c - y_f) - c_{ss}(\dot{y}_c - \dot{y}_f) - cm_f D^{1-\alpha}(\dot{y}_f - \dot{y}_s) - k_2 m_s sign(s) \quad (2.16)$$

Where $k_2$= n+$f_2$,

$$f_2 = -\frac{k_{ss}}{m_f}(y_f - y_s) - \frac{c_{ss}}{m_f}(\dot{y}_f - \dot{y}_s) + \frac{k_c}{m_f}(y_c - y_f) + \frac{c_c}{m_f}(\dot{y}_c - \dot{y}_f) \quad (2.17)$$

*3.2 Design of Terminal Sliding Mode Control*

To design TSMC for the QCSD with SA, the state variables are chosen as shown in Equation (2.4) and (2.5). The terminal sliding surface S becomes

$$s = (\dot{x}_1)^{\frac{p}{q}} + cx_1 \quad (2.18)$$

where p and q are integers which satisfy the condition p < q < 2p

Taking derivative of Equation (2.18)

$$\dot{s} = \frac{p}{q}(\dot{x}_1)^{\frac{p}{q}-1}\dot{x}_2 + c\dot{x}_1 \quad (2.19)$$

As per the Equation(2.6)

$$0 = \frac{p}{q}(\dot{x}_1)^{\frac{p}{q}-1}\dot{x}_2 + c\dot{x}_1 \quad (2.20)$$

By substituting the state variables in the above equation, the $f_s$ becomes $f_{s\_equ}$ and it is shown as follows

$$f_{a\_equ} = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s \frac{q}{p}(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} \quad (2.21)$$

Hence the desired control force $u_s$ is,

$$f_a = f_{a\_equ} - k_1 m_S sign(s) \quad (2.22)$$

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s \frac{q}{p}(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} - k_1 m_S sign(s) \quad (2.23)$$

In case of the QCSD with DA the Equation (2.23)is modified as

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) + f_b - cm_s \frac{q}{p}(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} - k_1 m_S sign(s) \quad (2.24)$$

To design the integrated seat suspension active force $u_f$ the state variables are as per the Equation(2.13) and (2.14). The terminal sliding surface is chosen as per the equation (2.18) and the sate variables are substituted. The equivalent control force derived from above equation is,

$$f_{b\_equ} = k_{ss}(y_f - y_s) + c_{ss}(\dot{y}_f - \dot{y}_s) - k_c(y_c - y_f) - c_c(\dot{y}_c - \dot{y}_f) - cm_f \frac{q}{p}(\dot{y}_f - \dot{y}_s)^{2-\frac{p}{q}} \quad (2.25)$$

Hence the desired control force is,

$$f_b = f_{b\_equ} - k_2 m_S sign(s) \quad (2.26)$$

$$f_b = k_{ss}(y_f - y_s) + c_{ss}(\dot{y}_f - \dot{y}_s) - k_c(y_c - y_f) - c_c(\dot{y}_c - \dot{y}_f) - cm_f \frac{q}{p}(\dot{y}_f - \dot{y}_s)^{2-\frac{p}{q}} - k_2 m_f sign(s) \quad (2.27)$$

*3.3 Design of Fractional order Terminal Sliding Mode Control*

To design FOTSMC for the QCSD with SA, the fractional order terminal sliding surface is chosen as follows,

$$S = (D^{\alpha}x_1)^{\frac{p}{q}} + cx_1 \quad (2.28)$$

where $D^{\alpha}$ (.) is the fractional calculus with 0 <α <1

Taking derivative of Equation (2.28)

$$\dot{S} = \frac{p}{q}(D^{\alpha-1}\dot{x}_1)^{\frac{p}{q}-1} D^{\alpha-1}\dot{x}_2 + c\dot{x}_1 \quad (2.29)$$

As per the equation (3.6)

$$0 = \frac{p}{q}(D^{\alpha-1}\dot{x}_1)^{\frac{p}{q}-1} D^{\alpha-1}\dot{x}_2 + c\dot{x}_1 \quad (2.30)$$

The state variables are chosen as per the Equation (2.4) and (2.5). By substituting the state variables and simplification the equivalent control force is,

$$f_{a\_equ} = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s \frac{q}{p}(D^{1-\alpha})(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} \quad (2.31)$$

Hence the desired control force is,

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) - cm_s \frac{q}{p}(D^{1-\alpha})^{\frac{p}{q}}(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} - k_1 m_s sign(s) \quad (2.32)$$

In case of the QCSD with DA the Equation (2.32) is modified as

$$f_a = k_s(y_s - y_u) + c_s(\dot{y}_s - \dot{y}_u) - k_{ss}(y_f - y_s) - c_{ss}(\dot{y}_f - \dot{y}_s) + f_b - cm_s \frac{q}{p}(D^{1-\alpha})^{\frac{p}{q}}(\dot{y}_s - \dot{y}_u)^{2-\frac{p}{q}} - k_1 m_s sign(s) \quad (2.33)$$

$x_1$ and $x_2$ are chosen as shown in the Equation (2.13) and (2.14), and the sliding surface is as per Equation (2.28) By substituting the state variables and simplification, the equivalent control force is

$$f_{b\_equ} = k_{ss}(y_f - y_s) + c_{ss}(\dot{y}_f - \dot{y}_s) - k_c(y_c - y_f) - c_c(\dot{y}_c - \dot{y}_f) - cm_f \frac{q}{p}(D^{1-\alpha})^{\frac{p}{q}}(\dot{y}_f - \dot{y}_s)^{2-\frac{p}{q}} \quad (2.34)$$

$$f_b = k_{ss}(y_f - y_s) + c_{ss}(\dot{y}_f - \dot{y}_s) - k_c(y_c - y_f) - c_c(\dot{y}_c - \dot{y}_f) - cm_f \frac{q}{p}(D^{1-\alpha})^{\frac{p}{q}}(\dot{y}_f - \dot{y}_s)^{2-\frac{p}{q}} - m_f k_2 sign(s) \quad (2.35)$$

## 4. Numerical simulation and results

The QCSD with SA and QCSD with DA are simulated separately in SIMULINK blocks of MATLAB R2012b. The QCSD parameters used in this work are from [7] and summarized in the Table I. While testing the performances of the QCSD, the system is subjected to three types of road inputs. All the three controllers are designed with the single bump [7] as the road input, then tested with other two types of road inputs without any modification in the controllers. The second type of road profile chosen for analysis is the sinusoidal road and the third type is the random road profile [13]. The road profiles are shown in Figure 2 and simulation are performed for the period of 2 seconds for all the cases.

While designing the SMC, λ is chosen as 2.5, α is chosen as 0.85 and n=0.00001, p=23 and q=23.23 to obtain the desired response. The same SMC parameters are used for all cases.

The Head Acceleration (HA) of the driver is the final control element considered for analysis. The performance of the controllers are compared in two different cases. The first one is the QCSD with SA and the second one is the QCSD with DA. Initially the controllers are designed and tested for the QCSD with SA and single bump road input. The Figure 3 shows that the passive response of HA of QCSD with SA. The time response of the HA is plotted for controllers with single bump input (Figure 4). The force produced by the SA is shown in Figure 5.

Table 1. Parameters used for quarter car with driver model

| Mass (Kg) | | Damping coef-ficient (Ns/m) | | Spring stiffness (N/m) X $10^3$ | |
|---|---|---|---|---|---|
| $m_u$ | 20 | $c_t$ | 0 | $k_t$ | 180 |
| $m_s$ | 300 | $c_s$ | 2000 | $k_s$ | 10 |
| $m_f$ | 15 | $c_{ss}$ | 830 | $k_{ss}$ | 31 |
| $m_c$ | 1 | $c_c$ | 200 | $K_c$ | 18 |
| $m_1$ | 12.78 | $c_1$ | 2064 | $k_1$ | 90 |
| $m_2$ | 8.62 | $c_2$ | 4585 | $k_2$ | 162.8 |
| $m_3$ | 28.49 | $c_3$ | 4750 | $k_3$ | 183 |
| $m_4$ | 5.31 | $c_4$ | 400 | $k_4$ | 310 |

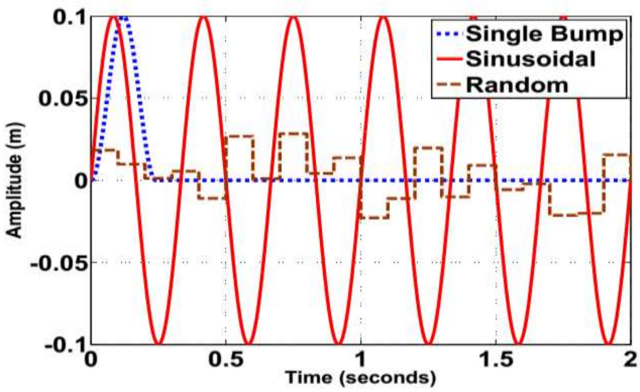

Figure 2. Road Profiles

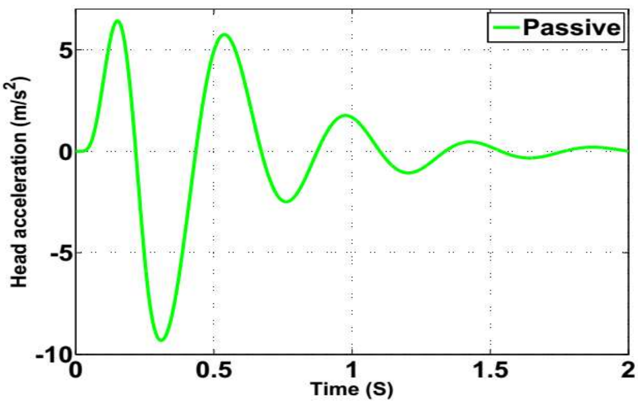

Figure 3. Passive response of the HA for single bump

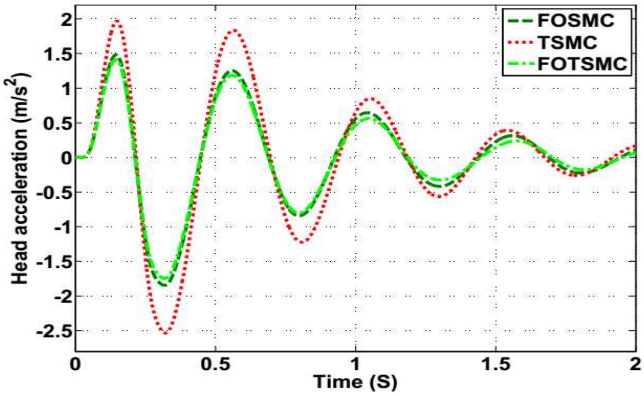


Figure 4. Time response of the HA for single bump road input in QCSD with SA

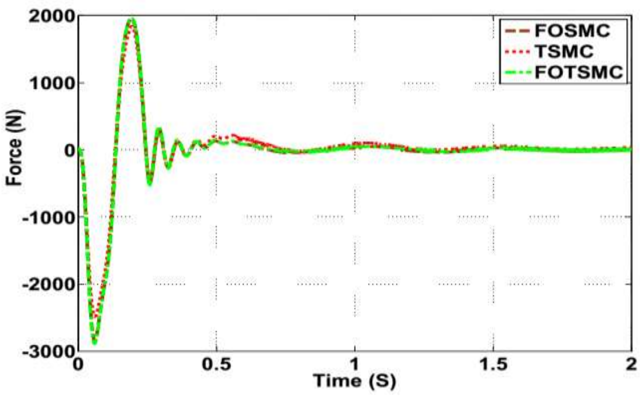


Figure 5. Force produced for single bump in QCSD with SA

Table 2. RMS values of HA for different road profile (m/s2)

| | | Types of Road inputs | | |
|---|---|---|---|---|
| | | Single bump | Sinusoidal | Random |
| SA | Passive | 2.957 | 11.44 | 1.447 |
| | FOSMC | 0.6887 | 2.061 | 0.3100 |
| | TSMC | 0.9528 | 2.814 | 0.4122 |
| | FOTSMC | **0.6453** | **1.958** | **0.2919** |
| DA | FOSMC | 0.2016 | 1.128 | 0.1488 |
| | TSMC | 0.2523 | 1.452 | 0.1641 |
| | FOTSMC | **0.1946** | **1.083** | **0.1484** |

The performance of the QCSD with DA is analyzed for the single bump input. The Figure 6 shows the time response of HA for single bump input for the QCSD with DA. The force produced by the active seat and active car suspension are shown in Figure 7 and Figure 8 respectively. From the RMS values (shown in Table II) of the time response of the HA, the FOSMC reduces the HA of the QCSD with DA by 16.47 % better than the QCSD with SA. Similarly the TSMC and FOTSMC reduces the HA of the QCSD with DA by 23.69 % and 15.24% better than the QCSD with SA respectively.

In DA the car suspension system has the saturation level of 1500 N [7]. This saturation level is not considered in SA and the force produced by the controller is more and the performances are less compared with the DA. In DA the control force is distributed in car suspension as well as in the seat suspension. The car suspension takes the primary control action up to its maximum limits and the remaining control force is supplied from the seat suspension. Therefore the control action in DA is better than SA.

When the performance of the controllers are compared with each other the FOTSMC reduces HA by 93.41% in QCSD with DA and 76.71% in QCSD with SA, which is better than FOSMC (93.18% and 76.71%) and TSMC (91.47% and 67.79%) in QCSD with DA and QCSD with SA respectively. Since the performance of the FOTSMC is better than the other controllers, the Figure 9 ccompares the performance of the FOTSMC in DA and SA

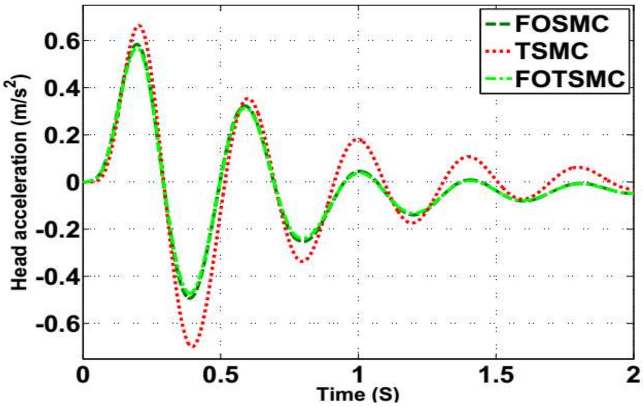


Figure 6. Time response of the HA for single bump road input in QCSD with DA

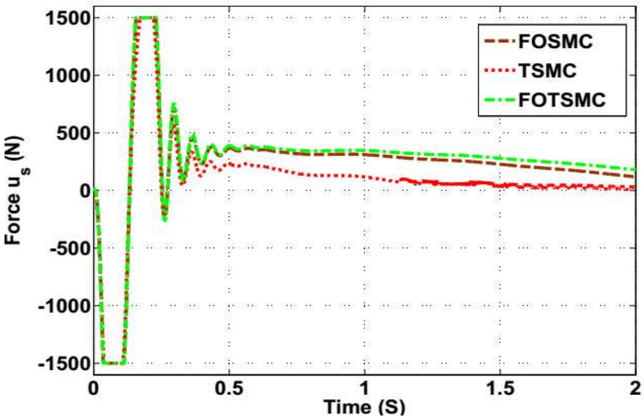

Figure 7. Force $u_s$ produced for single bump road input

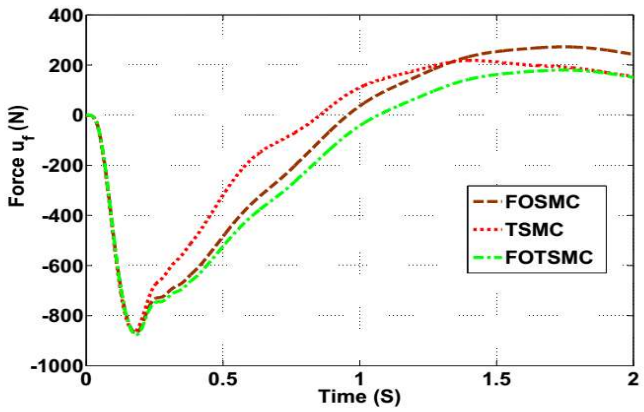

Figure 8. Force $u_f$ produced for single bump road input

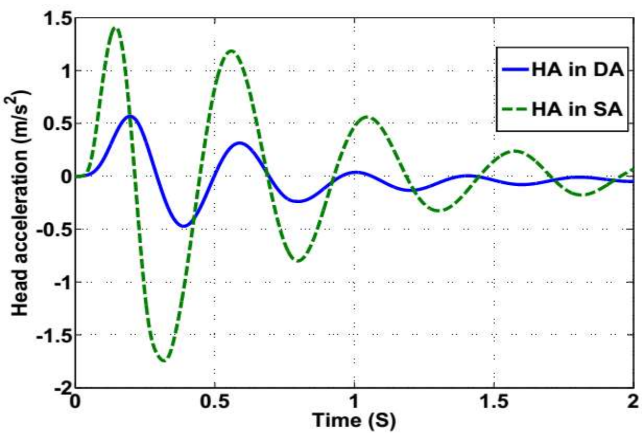

Figure 9. Performance of FOTSMC for single bump

In a road surfaces the speed breakers are placed to force the vehicle to reduce the speed. These speed breakers are modeled as the sinusoidal road input and the performance of the controller are tested.

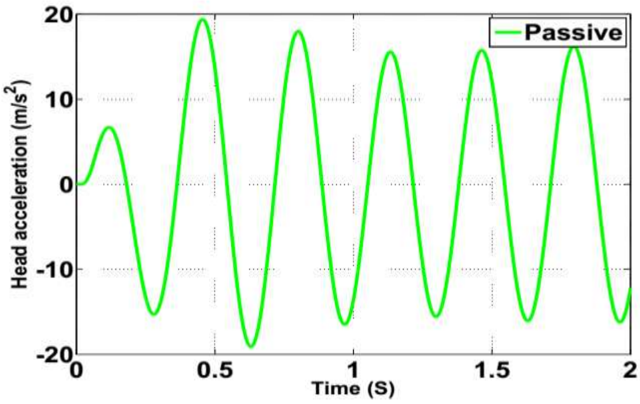

Figure 10. Passive response of the HA for sinusoidal road

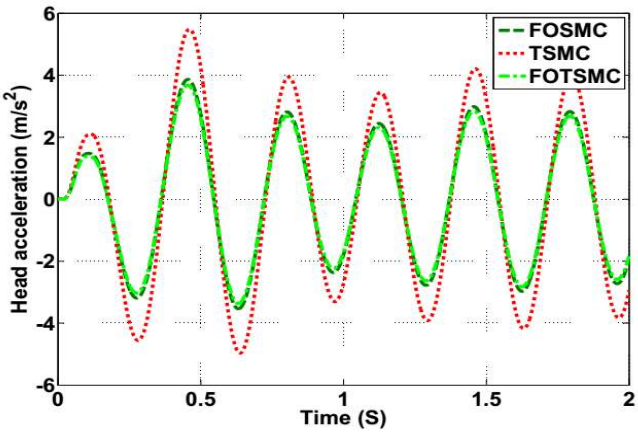

Figure 11. Time response of the HA for sinusoidal road input in QCSD with SA

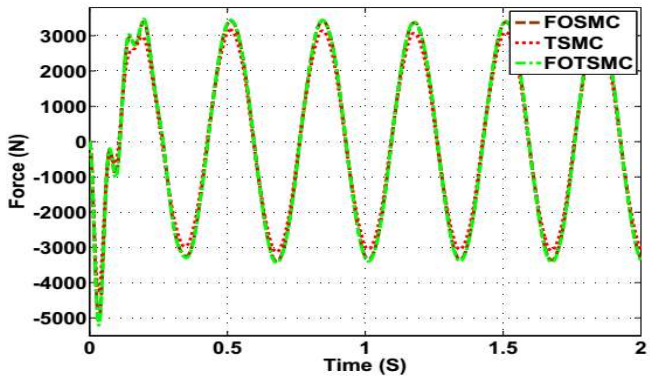

Figure 12. Force produced for sinusoidal raod in QCSD with SA

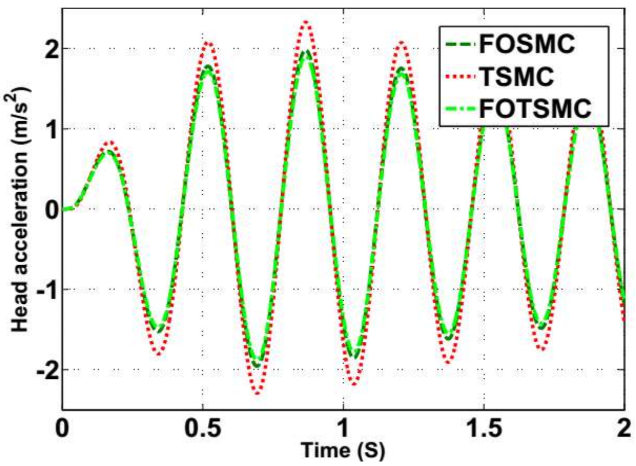


Figure 13. Time response of the HA for sinusoidal road input in QCSD with DA

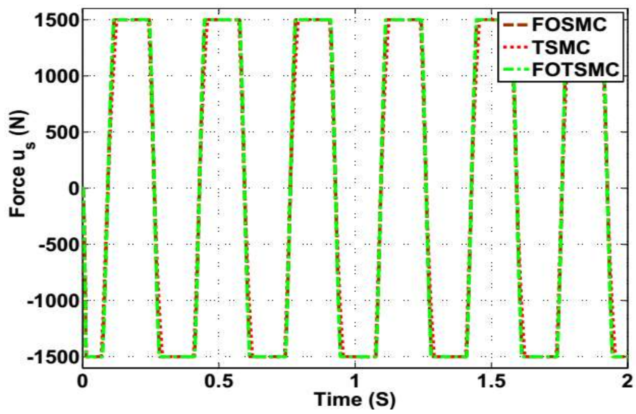


Figure 14. Force $u_s$ produced for sinusoidal road input

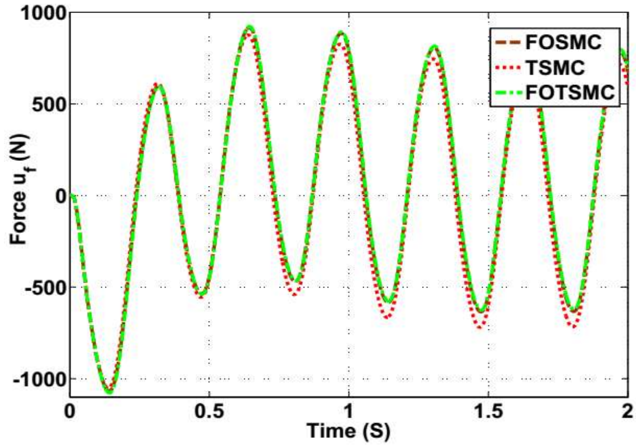


Figure 15. Force $u_f$ produced for sinusoidal road input

In this case the road input has the positive and negative magnitudes therefore the passive response (shown in Figure 10) of the QCSD and the time response with the controllers for QCSD with SA (shown in Figure 11) has high in magnitude with respect to single bump. The force produced by the controllers (shown in Figure 12) are also high compared with the single bump input. Similar to the single bump road input, the performances of the controllers in DA is better than the SA for sinusoidal road input. From the RMS values, the FOSMC reduces the HA of the QCSD with DA by 8.16 % better than the QCSD with SA. Similarly the TSMC (by 11.91 %) and FOTSMC (7.65%) reduces the HA of the QCSD with DA than the QCSD with SA.

When the performance of the controllers are compared with each other the FOTSMC reduces HA by 90.53% in QCSD with DA and 82.88% in QCSD with SA, which is better than FOSMC (90.14% and 81.98%) and TSMC (87.31% and 75.4%) in QCSD with DA and QCSD with SA respectively.

Figure 13, Figure 14 and Figure 15 shows the time response of the HA for QCSD with DA and sinusoidal input, the active control force produced by the seat suspension and car suspension respectively.

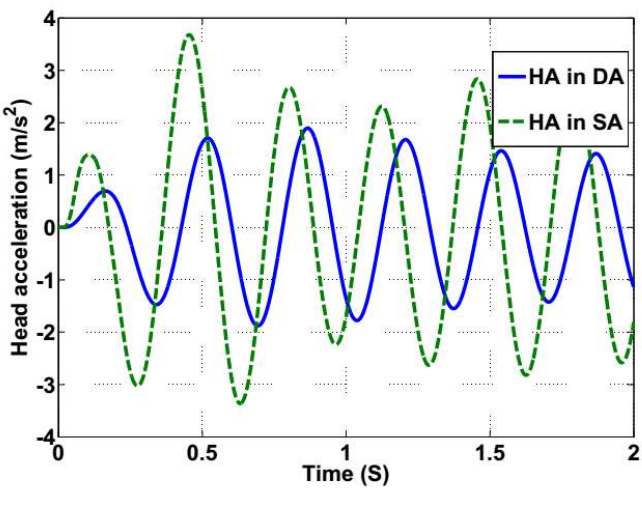


Figure 16. Performance of FOTSMC for sinusoidal road

The Figure 16 compares the performance of the FOTSMC in DA and SA for the sinusoidal road input and shows the effectiveness of the DA.

As the road surfaces are not uniform, any kind of disturbances are expected from the road. Therefore it is necessary to consider the random road profiles and test the performance of the controllers. As the road inputs are randomly changing in 0.1 seconds, the control action should be quick enough to handle the changes and hence it requires higher magnitude of the force. As the road disturbance is random in nature the passive response of the QCSD is also random in nature as shown in Figure 20.

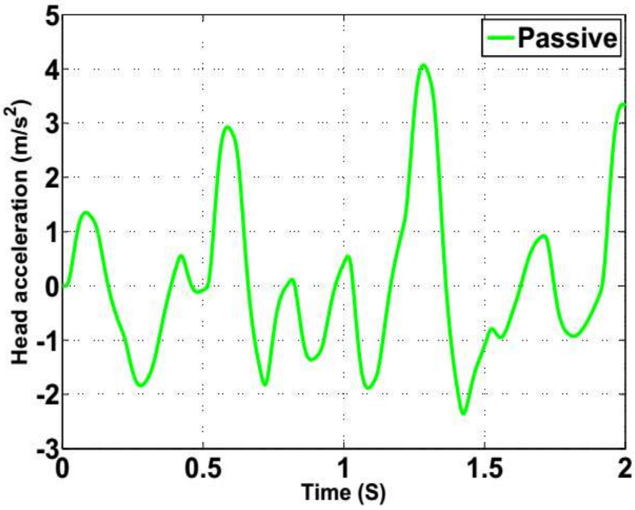


Figure 20. Passive response of the HA for random road

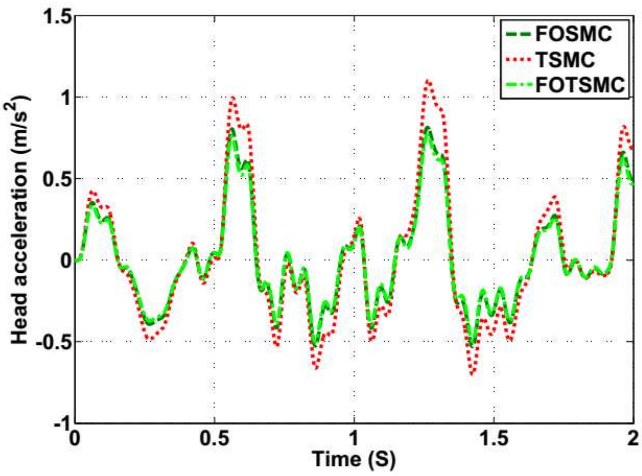


Figure 21. Time response of the HA for random road input in QCSD with SA

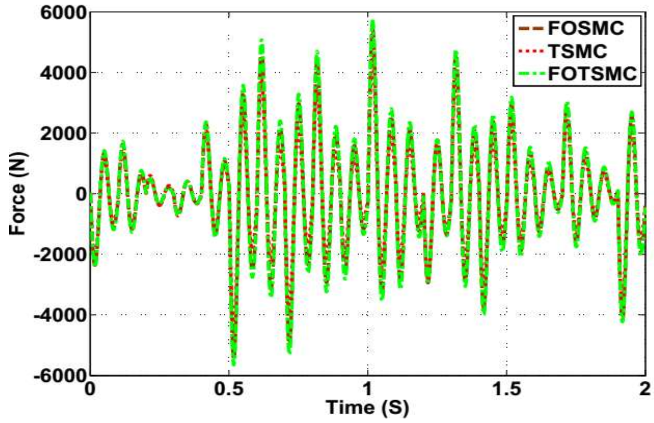


Figure 17. Force produced for random road in QCSD with SA

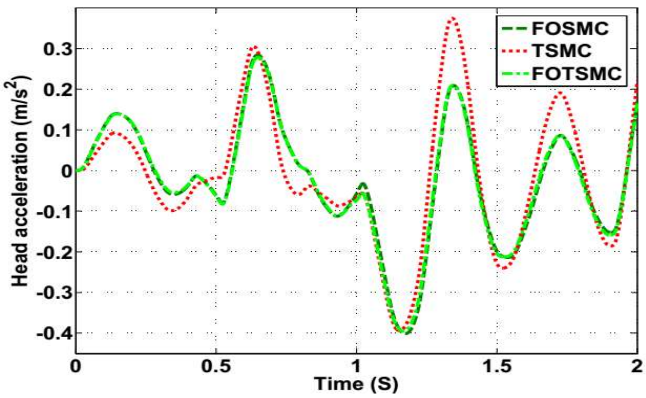


Figure 18. Time response of the HA for random road input in QCSD with DA

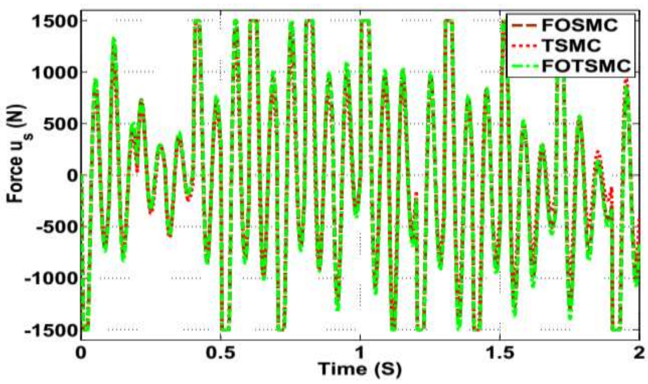


Figure 19. Force $u_s$ produced for random road input

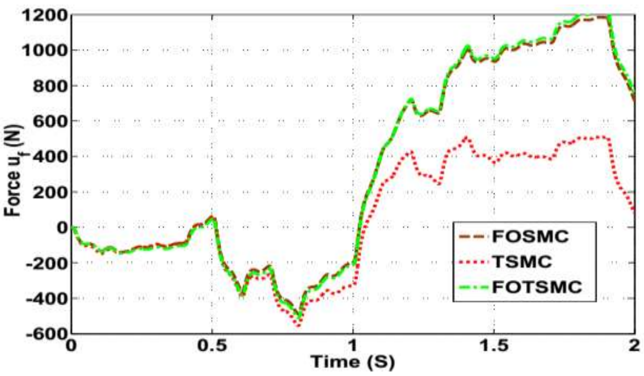


Figure 22. Force $u_f$ produced for random road input

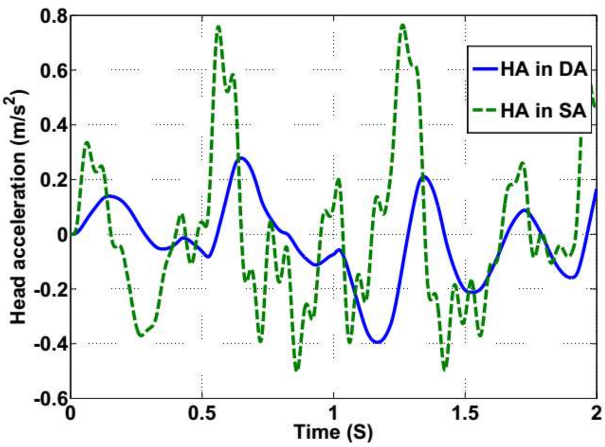


Figure 23. Performance of FOTSMC for random road

Similar to the other two road profiles considered so far, the performances of the controllers in DA is better than the SA for random road input. From the RMS values of the time response of the HA, the FOSMC reduces the HA of the QCSD with DA by 11.14 % better than the QCSD with SA (Figure 21). Similarly the TSMC (by 17.15 %) and FOTSMC (9.92 %) reduces the HA of the QCSD with DA than the QCSD with SA. Figure 17 shows the force produced by the SA for random road input.

Figure 18, Figure 19 and Figure 22 shows the time response of the HA for QCSD with DA for random road input, the active control force produced by the seat suspension and car suspension respectively. While comparing the performance of the controllers with each other, the FOTSMC reduced HA by 89.74% in QCSD with DA and 79.83% in QCSD with SA, which is better than TSMC (88.87% and 71.51%) and FOSMC (89.71% and 78.58%) in QCSD with DA and QCSD with SA respectively.

Figure 23 compares the performance of the FOTSMC in QCSD with DA and SA for the random road profile. From the response, it is inferred as the DA controller HA better than the SA for the random road profiles.

The vehicle ride quality is analyzed with respect to Power Spectrum Density (PSD) and plotted for the HA in QCSD with DA (Figure 24 to Figure 26) as a function of frequency for all three types of road profiles. FOTSMC reduced HA effectively in the human sensitive frequency range [2] of 4 to 8 Hz for all the road profiles

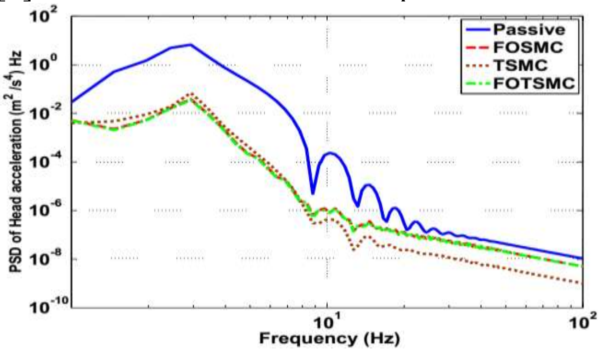


Figure 24. PSD of HA in single bump in QCSD with DA

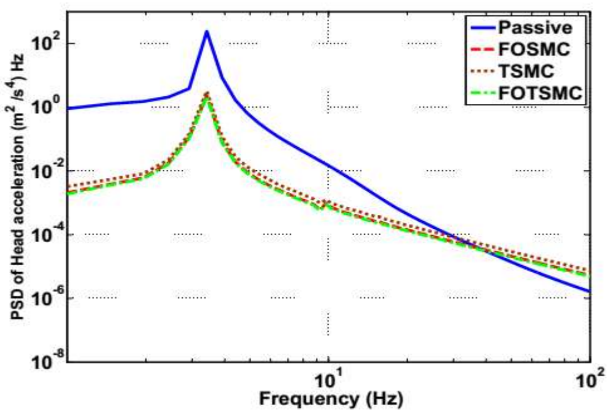


Figure 25. PSD of HA in sinusoidal raod input in QCSD with DA

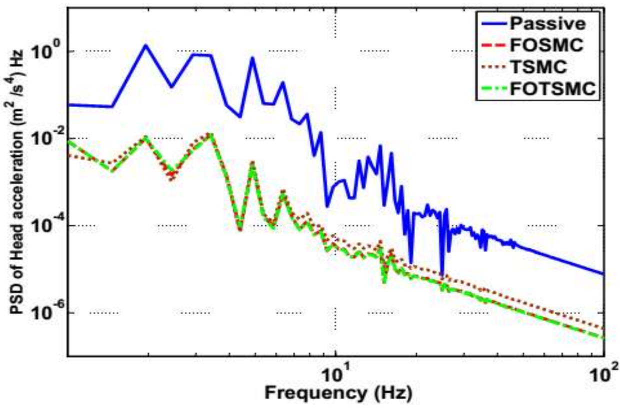


Figure 26. PSD of HA in random road input in QCSD with DA

## 5. Conclusion

The vibration control strategies for the QCSD with SA and DA are designed and simulated for FOTSMC. The performances of the FOTSMC are compared against the TSMC, FOSMC and passive system. The results are analyzed in terms of RMS and PSD. When the DA and SA are compared, the FOSMC for QCSD with DA reduces the HA by 11.92% then QCSD with SA. Similarly the TSMC and FOTSMC in QCSD with DA reduces the HA by 17.58% and 10.94 % respectively. Therefore the QCSD with DA performs better than the QCSD with SA. While the performance of the controllers in QCSD with DA are compared, the FOTSMC is 4.95 % better than the FOSMC and 0.84% better than TSMC. In the case of QCSD with SA, the FOTSMC reduces the HA by 1.21% better than the FOSMC and by 8.73% better than the TSMC. FOTSMC outperforms the other controllers in all the road inputs.

The driver or passenger mass can be considered as the variable mass and this condition is called as the perturbed condition. These SMCs and other types of advanced SMCs such as Fuzzy based SMC and integral SMCs can be designed for the system with perturbed condition and further analysis is possible.

## 6. References


1 Bart L. J. Gysen, Tom P. J. van der Sande, Johannes J. H. Paulidesb and Elena A. Lomonova: “Efficiency of a Regenerative Direct-Drive Electromagnetic Active Suspension”, *IEEE Transactions On Vehicular Technology*, volume 60, No. 4, pp. 1384-1393. May 2011.

2 Kalaivani R, Lakshmi P and Sudhagar K.: “Hybrid (DEBBO) Fuzzy logic Controller for Quarter Car Model” *IEEE International Conference on Control*, pp. 301-306, 2014.

3 Rajeswari, K., and Lakshmi, P.: Vibration control of mechanical suspension system, *International Journal of instrumentation Technology*, no.1, pp.60-71, 2011.

4 Tinnavelli Ramamohan Rao and Punjala Anusha: “Active suspension system of a 3 DOF quarter car using fuzzy logic control for ride comfort”, *IEEE international conference on Control, Automation, Robotics and Embedded Systems,* 2013.

5 Haiping Du, Weihua Li, and Nong Zhang: “Vibration control of vehicle seat integrating with Chassis Suspension and Driver Body Model”, *Advances in Structrual Engineering*, volume 16, No.1, pp 1-9, 2013.

6 SaeedBadran, Ashraf Salah, Wael Abbas and Ossama B. Abouelatta: “Design of optimal linear suspension for quarter car with human model using genetic algorithms”, *The research bulletin of Hourdan ACM,* volume II(II), pp. 142- 151, 2012.

7 Haiping Du, Weihua Li, and Nong Zhang: “Integrated Seat and Suspension Control for a Quarter Car with Driver Model”, *IEEE transactions on vehicular technology,* volume, 61, No. 9, pp. 3893-3908, November 2012.

8 Ayman A. Aly, and Farhan A. Salem: “Vehicle Suspension Systems Control: A Review”, *International journal of control, automation and systems,* volume 2 No.2, pp. 46-54, 2013.

9 S.-B. Choi, Y.-M. Han: “Vibration control of electrorheological seat suspension with human-body model using sliding mode control”, *Journal of Sound Vibration*, volume 303, No. ½, pp. 391–404, 2007.

10 O. Gundogdu: "Optimal seat and suspension design for a quarter car with driver model using genetic algorithms," *International Journal of Industrial Ergonomics*, Vol. 37, No. 4, pp. 327-332, Apr. 2007.

11 A. Kuznetsov, M. Mammadov, I. Sultan, and E. Hajilarov: "Optimization of a quarter-car suspension model coupled with the driver biomechanical effects," *Journal of Sound Vibration,* volume 330, No. 12, pp. 2937–2946, 2011

12 Rajeswari K, Lavanya S., and Lakshmi P.: "Grey Fuzzy sliding Mode controller for Vehicle Suspension System" *Control Engineering and Applied Informatics* volume 17, No.3 pp. 12-19, 2015.

13 R. Kalaivani, P. Lakshmi and K. Rajeswari: "An improved type-2 fuzzy logic approach based sliding mode controller for vehicle active suspension system", *Journal of Vibration Engineering & Technologies*, volume 14, No.4, pp. 431-446, 2015.

14 Ayman A. Aly: "Robust Sliding Mode Fuzzy Control of a Car Suspension System", *International Journal of Information Technology and Computer Science*, volume 08, pp. 46-53, 2013.

15 Hung-Yi Chen A and Shiuh-Jer Huang: "A new model-free adaptive sliding controller for active suspension system", *International Journal of Systems Science* volume 39, No. 1, pp. 57–69, January 2008.

16 Ervin Alvarez-Sánchez: "A quarter-car suspension system: car body mass estimator and sliding mode control", *Conference on Electronics Engineering and Computer Science, Procedia Technology,* volume 7, pp. 208 – 214, 2013.

17 Yingchun Long and Lifu Li: "Fuzzy Fractional Order Sliding Mode Control for Automatic Clutch of Vehicle AMT", *International Journal of Smart Home*, volume 9, No. 2, pp. 53-68, 2015.

18 Yinggan Tang, Xiangyang Zhang, Dongli Zhang, Gang Zhao and Xinping Guan, M.: "Fractional order sliding mode controller design for antilock braking systems", *Neurocomputing,* volume111, pp. 122–130, 2013.

19 Jiacai Huang, Hongsheng Li, YangQuan Chen and Qinghong Xu.: "Robust Position Control of PMSM Using Fractional-Order Sliding Mode Controller" *Abstract and Applied Analysis*, Article ID 512703, 33 pages, 2012.

20 Mehmet Onder EFE. Fractional order sliding mode control with reaching law approach, *Turk Journal of Electrical Engineering and Computer Science,* Vol.18, No.5, 2010.

21 Minh-Duc Tra and Hee-Jun Kang: "Nonsingular Terminal Sliding Mode Control of Uncertain Second-Order Nonlinear Systems", *Mathematical Problems in Engineering*, Article ID 181737, 8 pages, 2015.

22 Mou Chen, Qing-Xian Wu and Rong-Xin Cui: "Terminal sliding mode tracking control for a class of SISO uncertain nonlinear systems", *ISA Transactions* 52, pp. 198–206, 2013.

23 Jeng-Dao Lee, Suiyang Kho and Kwei-Yuan Lai: "*Terminal Sliding Mode Control Strategy Design for Second-order Nonlinear System"* Proceedings of the 38th Annual Conference on IEEE Industrial Electronics Society, Piscataway, N.J., E1 pp. 2512-2517, 2012.

24 Sara Dadras and Hamid Reza Momeni: "*Fractional terminal sliding mode control design for a class of dynamical systems with uncertainty",* Commun Nonlinear Sci Numer Simulat 17, pp. 367–37, 2012.

25 Jean-Jacques E. Slotine and Weiping Li: *Applied Nonlinear Control*, Prentice Hall, New Jersey, 1991.

26 Jinkun Liu and Xinhua Wang: "Advanced Sliding Mode Control for Mechanical Systems", *Tsinghua University Press*, Beijing and Springer-Verlag Berlin Heidelberg 2011.

27 Nasim Ullah, Wang Shaopingb, Muhammad Irfan Khattak and Muhammad Shafid : "Fractional order adaptive fuzzy sliding mode controller for a position servo system subjected to aerodynamic loading and nonlinearities", *Aerospace Science and Technology,* volume 43, pp.381-387, 2015.