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Vibrational Behaviour of a Quarter Car Travelling over Road Humps with Different Suspension Systems

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I. INTRODUCTION

During the last century, the vehicle has become one of the basics of daily life. Wherever we are, the vehicle is considered as the companion of man in all parts of the earth. Wherever the human found the vehicle inherent to him. The vehicle is one of the ways to add more comfort and ease human life. Since the beginning of the production of vehicles, scientists and vehicle manufacturers have been interested in ride comfort as one of the most important factors in adding driving a pleasure.[1]

Due to the unawareness of some vehicles' drivers to abide by the limited speeds, many authorities have had to set up road speed humps to calm down the vehicle's flow, especially in densely populated areas. And as a result, bad vehicle ride comfort is produced for the vehicle components.[2]

Semi-active suspension is a type of vehicle suspension system in which the force generated by the damping is variable to achieve better ride comfort and reduce the amplitude of the shock amplitude of the generated vibrations. The damping force is varied depending on the input outgoing naturally changing road surfaces. The purpose of this system is to apply the adaptive active suspension using variable shock absorbers that produce variable damping force. The semi-active suspension system can be managed in a variety of control methodologies. One of these methods is a rather ideal technology referred to as the Skyhook control system .[3]

As for the active suspension system, it is fundamentally different from other previous types, as it depends mainly on a control system that works to regulate the generation of additional power that is produced by an electrical or hydraulic actuator organized by a control algorithm based on the signals of the sensors indicating the road and driving conditions of the vehicle. In addition to the main suspension components; spring and damper; the active suspension includes the actuator to provide additional force to spring and damper forces that contribute to improving ride comfort. The active suspension is characterized by the generation of additional power from the actuator to reduce the impact of vertical forces generated by unexpected changes in road inputs.[4]

There are two main types of humps, the short type which is known as bumps that are typically used to smooth lanes in low-speed areas such as school fronts and shopping mall parking lots. This type of bump is designed to force cars to travel at extremely low speeds less than10 km/h. As for the other type of humps, it is to slow down traffic on a larger scale and is characterized by its large dimensions, relatively to the short type, and is used in the streets within the city to force cars over a range of 10-20 km/h. The humps usually lead to a sharp jolt in the car's suspension system, especially the short bumps, and it can reach severe damage to the

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suspension system if the driver tries to cross at speeds much greater than the established speed limits. It is necessary to design warning signs and lights before the hump to warn of the presence of a bump. There is a third type of bumps called the cat-eye hump, which is often used as a warning sign of an emergency, and this variety of road humps significantly worsens the ride comfort .[5]

To reach an optimal solution that guarantees the safety of driving on the roads inside the city, while obtaining an acceptable riding comfort, the car manufacturers tried to implement an intelligent system that is characterized by alignment in the suspension system to achieve the highest possible ride comfort. One of these systems is the active and semi-active suspension system. Therefore, the aim of this research is to study the vibrational behaviour of vehicle suspension system when the vehicle over humps using mathematical equations modelled in MATLAB Simulink. The research objectives are to create mathematical models for the vehicle and hence to build these models in MATLAB Simulink and then study to optimize the most used vehicle suspension system that gives the best ride comfort.

The road hump is an extension designed over the road to calm down the traffic flow. Many hump profiles are globally used. The circular hump is the most widespread one that is used on city roads. The circular hump is the most famous hump used in vehicle roads because of its design simplicity and its reasonable effectiveness. The circular hump is characterized by hump width and height. The recommended hump width is not less than 3-4 m while the maximum height is 10-15 cm. Recommended circular humps height is about 10 cm. Heights less than the assumed 10 cm will result in that the hump is not effective. Heights above 10 cm may cause severe damage to vehicles [1].

To force vehicle drivers to calm down the speed, there are several types of common road humps, such as speed bumps, speed humps, speed cushions, speed tables, and chicane.[2]

Abdulmawjoud et al. [5] have studied the drivers' behaviour when the vehicle is travelling over three main types of standard humps, which are single circular hump, double circular humps, and trapezoidal hump. The traffic calm installed along the main roads of one of the cities was studied, and they found that the rate of decrease in the vehicle speed reached more than 70% when the vehicles are travelling over the humps. It was noted that the trapezoidal hump causes a greater decrease in speed than the other species studied, with a decrease of approximately 80%. In terms of ride comfort, the worst ride comfort was recorded in the case of a single circular hump.

Pozuelo et al. [6] have presented theoretical and experimental study to investigate the vehicle vibrational behaviour when the vehicle is travelling over a circular hump. The main goal of the model and software that to introduce a prediction of the vertical dynamics of a vehicle when traveling over a hump using a half-car model. They also developed mathematical expressions to formulate the displacement behaviour resulting from the movement of the vehicle over the circular hump. The model signals are validated by comparing with the recorded experimental results of maximum vertical acceleration, maximum longitudinal pitch angle, maximum dynamic tire load of the front suspension, maximum dynamic tire of the rear suspension. The results showed that driving the vehicle over the hump leads to a severe deterioration in the ride comfort, as well as the stability parameters of the vehicle, especially at high speeds.

In another way, Mahmoud [7] presented the function of the circular hump in a simplified way, while he represented the rectangular hump as a function of the height and length of the hump and the speed of the vehicle. He presented the riding comfort factors as the suspension working space, the vertical body acceleration, and dynamic tire load as factors comparing the ride comfort and stability of the car on the road.

The suspension system of the vehicles is an important part of obtaining satisfactory ride comfort, as well as one of the components of the vehicle's safety requirement. A suspension system typically contains shock absorbers and springs. The shock absorbers compress and rebound with the help of springs when a force is applied to them. The suspension system provides a safe driving experience for the driver, passengers, and occupants of the vehicle by reducing or eliminating body roll in turns, bumps in the road, and vibrations [8].

A passive suspension system is a system in which the basic components are used to isolate the vibrations resulting from the movement of the vehicle on the road, such as springs and dampers. The design and selection of the spring and damper are chosen according to the vehicle's operating conditions and according to the design objectives and intended application [9].

A semi-active suspension system is an application of mechatronics to a suspension system. A semi-active suspension system is characterized by a switchable damper, and the damping coefficient can be adapted according to the driving conditions. The vehicle's ride comfort with a semi-active suspension system is improved in comparison with a passive suspension system. Vehicle stability is also performed with a semi-active suspension system when compared with a passive system [10-12].

To study the vibrational behaviour of the vehicle while travelling over roads, there are many methods to represent the road signals. Phalke et al. [13] have used the eccentric method of an external tire to generate the road excitation to the tire of a vehicle used as part of a quarter car model. This method has been applied in many previous studies such as Florin et al. [14] and Mehdi et al. [15].

Magnetorheological (MR) is one of the most recent and widely used applications in semi-active suspension systems. It consists of an intelligent device whose function is to dampen the vibrations to reach a relatively acceptable vibration amplitude that meets the requirements for vehicle ride comfort. Usually, the magnetorheological is based on the generation of a magnetic field using a direct current from the controller affecting the coil in the magnetorheological MR, and this causes the MR fluids to change from a viscous liquid state to a semi-solid state in the resistance gap [16-18].

The active suspension system is characterized by the presence of a linear actuator beside the spring and damper. The linear actuator can be either a hydraulic actuator or an electric motor. The role of the linear actuator is to generate the force required for the suspension system to be more comfortable and the vehicle more stable during varied driving conditions [19-21].

Modelling of vehicle suspension systems can be simulated as a quarter car, which deals with two degrees of freedom [22]. Two masses are used in the quarter-car model: a sprung mass and an unsprung mass. The sprung mass includes the chassis, body, engine, and cabin. The sprung mass is carried over the spring and damper system [23]. Un-sprung masses are the axle and tire masses and are installed down the spring and damper system [24]. The quarter model of vehicle suspension system performance can be introduced with sprung mass vertical acceleration, tire dynamic load, and suspension working space .[25]

To evaluate the vibrational behaviour of the vehicle while traveling over the bumps, Fakhraei et al. [28] assumed that the hump function is part of a sinusoidal wave for the circular humps, while for the rectangular humps, it was expressed as a function of the amplitude (height), the length of the bump and the frequency (vehicle speed). They studied the effect of traveling over humps on non-linear dynamic behaviours as well as ride comfort for the vehicle and driver. A mathematical model was presented, by solving the differential equations and then evaluating the ride comfort by calculating the RMS value of the vertical displacement of the vehicle body and the driver.

Other works have presented theoretical research aiming to reduce the cost of that which uses magnetorheological MR damper such as Ghoniem et al. [32] who have used a new, low-cost damper for the application of the vehicle's semi-active suspension systems. The strategy of this system is based on changing the damping coefficient is adapted using an artificial neural network controller by controlling the throttle opening area. A controller was trained based on the data obtained from the PID controller. The results showed that the proposed new suspension system provides a cheaper alternative to commercially available semi-active suspension systems based uses magnetorheological MR damper. The proposed new semi-active suspension could cost up to 20% of the cost of the magnetorheological MR damper.

In this work, to study the vehicle's vibrational behaviour, a mathematical model for a quarter of a vehicle was designed using the MATLAB Simulink program. Three models of passive, semi active and active suspensions were presented for use in this study. Comparison of the vibrational behaviour of the three types will be introduced when the vehicle is travelling over different types of road humps such as circular, trapezoidal, and cat eye hump to achieve the most ride comfortable system.

II. METHODOLOGY

To study the vehicle's vibrational behaviour, a mathematical model for a quarter of a vehicle was designed using the MATLAB Simulinkprogram. Three models of passive, semi active and active suspensions were presented for use in this study. Comparison of the vibrational behaviour of the three types will be introduced when the vehicle is travelling over different types of road humps such as circular, trapezoidal, and cat eye hump to achieve the most ride comfortable system.

MATLAB Simulink will be used in this study; a quarter car model will be investigated to achieve vibrational behaviours of the vehicle and these effects on vehicle ride comfort.

Moreover, a comparison between the three models will be introduced.

From the simulation results, we assume to find the following data for each case :

- Body Vertical Acceleration (m/s2).
- Tire Dynamic Loads (N).
- Suspensions Working Space (m).
- Body Displacement (m) .

Where these four outputs are directly affecting the ride comfort and stability of the vehicle. Moreover, the vibrational behaviours of the three types of suspension systems will be investigated.

A semi active suspension system is normally characterized by the presence of a control system. Mostly PID controller is used to adapt the body vertical acceleration within minimum level. The damping coefficient is used as the controller action. The proportional parameter $K_P$is firstly tuned. Then, the integrator factor $K_I$is adapted until the system noise reached until minimum levels and the error becomes too low. The differential parameter $K_D$is then adjusted to damp the noise of the signal. Saad et al [22] and Hanafi et al [23] have used PID controller in their work to control semi-active suspension system.

The active suspension system is characterized by the presence of a linear actuator beside the spring and damper. The linear actuator can be either a hydraulic actuator or an electric motor. The role of the linear actuator is to generate the force required for the suspension system to be more comfortable and the vehicle more stable during varied driving conditions [19-21].

Tremendous development has occurred in vehicle technology in most of the vehicle's components, especially the suspension system. Firstly, the suspension system has been presented in the economic vehicles as a major part of the vehicle's parts. The main role of the suspension system is to isolate or reduce the vibrations resulting from the movement of the vehicle is travelling over different roads according to the quality of the asphalt. Conventional suspension system is consisting of sprung mass and un-sprung mass connected by a spring and damper. The un-sprung mass is attached to the bottom by means of a tire stiffness. The conventional system is called the passive suspension system. To enhance the performance of the suspension system, a semi-active suspension system has been applied, in which the value of the damping coefficient is adapted based on changing operating conditions such as vehicle speed and road quality. Many references have proven the effectiveness of the semi-active suspension system.

On the other hand, the quality of roads in residential areas and highways is increasing day by day, which encourages some vehicle drivers to drive at high speeds more than the recommended limits set by the authorities. Therefore, decision makers have been forced to extend road humps, especially where accidents are frequent. Several shapes of humps and bumps have been presented such as circular, trapezoidal and circular bumps. Of course, these humps greatly affect the vehicle ride comfort, especially when traveling over them at high speeds.

Therefore, the aim of this work is to present a theoretical study (a mathematical model) using the MATLAB Simulink program to investigate the vibrational behaviour of a quarter a car with passive suspension and a semi-active suspension system with a comparison between each system when driving over the types of bumps by calculating - :

- Body Vertical Acceleration (m/s^2).
- Tire Dynamic Loads (N).
- Suspensions Working Space (m).
- Body Displacement (m).

III. Modeling & Analysis

Table 1: Below shows a medium sedan passenger car specification that will be used in this study.[6]

Table 1: Sedan vehicle specifications

Parameters	Value
Suspension Stiffness (k_s)	30000 (N/m)
Damping Coefficient (c_s)	3500 (N·s/m)
Sprung Mass (m_2)	381 (kg)
Un-Sprung Mass (m_1)	50 (kg)
Tire Stiffness (k_t)	220000 (N/m)
Tire Damping Coefficient (c_t)	140 (N.s/m)
Moment of Inertia (J)	1000 (kg.m^2)
Wheelbase (L)	2.69 (m)

Many types of road humps are globally used in urban areas. In this study, three well known types of road humps are used: circular hump, trapezoidal hump, and cat-eye hump.

a) Circular Hump

The circular humps are one of the common humps that are used in urban areas and cities. The circular hump is characterized by the arc radius “R”, the hump length, and hump height.

It is required to calculate the time required that the vehicle is travelling over the hump. The time is the input of the model. The time can be expressed as follow:

$$t = \frac{L}{v} \tag{1}$$

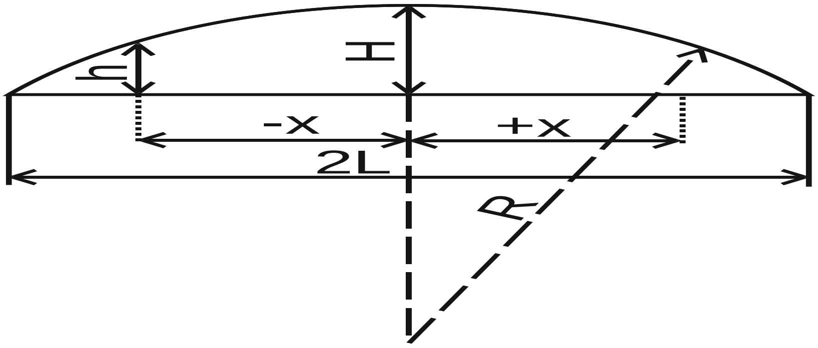

Figure 1: Circular hump profile

Fig. 1 shows the circular road hump profile where the radius R in meter and the length and the height of the hump.

$$R^2 = L^2 + (R - H)^2 \tag{2}$$

$$R = \frac{L^2 + H^2}{2H} \tag{3}$$

$$h = \sqrt{R^2 - x^2} - (R - H) \tag{4}$$

b) *Trapezoidal Hump*

Fig. 2 shows the configuration of the trapezoidal hump. The trapezoidal hump is characterized by total length “L”, inclined length “L_1”, flat top length “L2”, and hump height “H”.

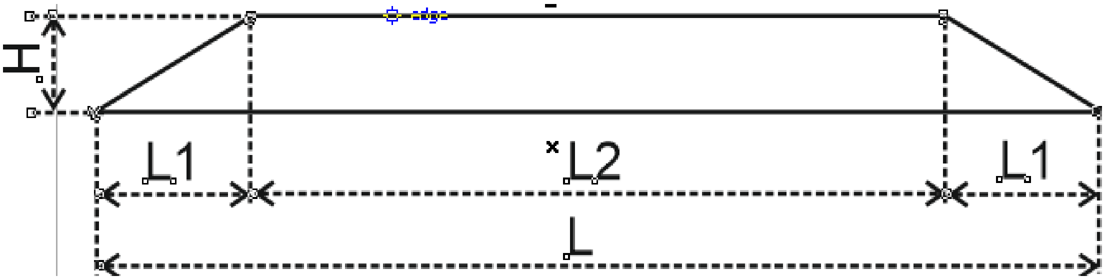

Figure 2: Trapezoidal hump profile

The hump height can be expressed as follow:

$$h = \begin{cases} H\frac{x}{L_1} & for \quad 0 < x < L_1 \\ H & for \quad L_1 < x < (L_1 + L_2) \\ H\frac{(x-L)}{L_1 + L_2 - L} & for \quad (L_1 + L_2) < x < L \end{cases} \tag{5}$$

c) *Cat-Eye Hump*

The cat-eye hump is arranged in a matrix configuration and distributed transversally to the roads. It is principally designed as a cushion or attention system. Fig. 3 shows the cat-eye hump configuration.

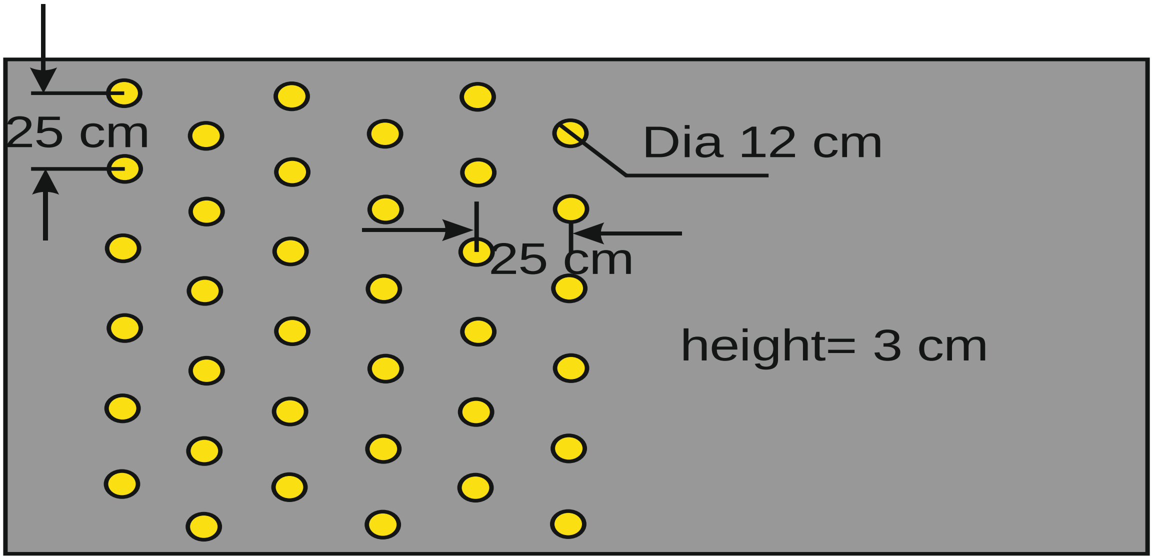

Figure 3: Cat-eye hump configuration

The same equations of circular hump can be applied with a cat-eye hump. It can be assumed that 6 columns of the cat-eyes are distributed with 25 cm intervals. Thus, the total distance is about 1.5 m. Table 2 below shows all types of humps with their specifications.[33]

Table 2: Circular, trapezoidal, and cat-eye humps specifications

Parameters / Type of Humps	Circular Hump	Cat-Eye Hump	Trapezoidal Hump
Maximum height (cm)	10.76	3.0	10
Length (m)	3.6	-	6.33
Arc radius (m)	15.11	0.075	-
Triangle length (m)	-	-	1.58
Top cat-eye diameter (cm)	-	12	-
Cat-eye horizontal interval (cm)	-	25	-

d) *Passive Suspension System*

Fig. 5 shows the configuration of the passive suspension system when the vehicle is travelling over a hump. The equations of motion can be expressed as follow:

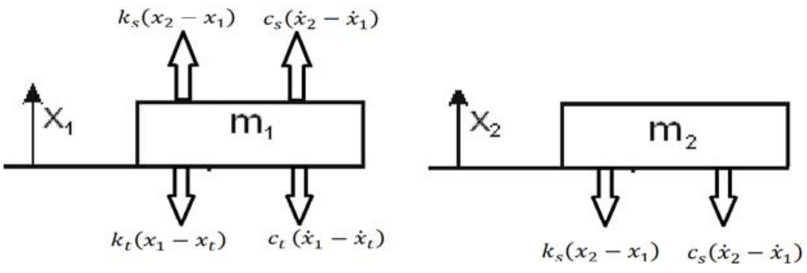

Figure 4: Free body diagram of passive system

For m_1:

$$m_1\ddot{x}_1 = k_s\left(x_2 - x_1\right) + c_s\left(\dot{x}_2 - \dot{x}_1\right) - k_t\left(x_1 - x_t\right) - c_t\left(\dot{x}_1 - \dot{x}_t\right)$$
$$m_1\ddot{x}_1 + (c_s + c_t)\dot{x}_1 - c_s\dot{x}_2 + (k_s + k_t)x_1 - k_s x_2 = k_t x_t + c_t \tag{6}$$

For m_2:

$$m_2\ddot{x}_2 =- c_s\left(\dot{x}_2 - \dot{x}_1\right) - k_s\left(x_2 - x_1\right)$$
$$m_2x_2 - c_s\ddot{x}_1 + c_s\dot{x}_2 - k_s\dot{x}_1 + k_s x_2 = 0 \tag{7}$$

Where,
m_1 *is the unprung mass,*
m_2 *is the sprung mass,*
x_1 *is unsprung mass displacement,*
x_2 *is the sprung mass displacement,*
Cs is sprung damper,
Ct is unsprung damper,
Ks is sprung stiffenes and
Kt is unsprung stiffenes

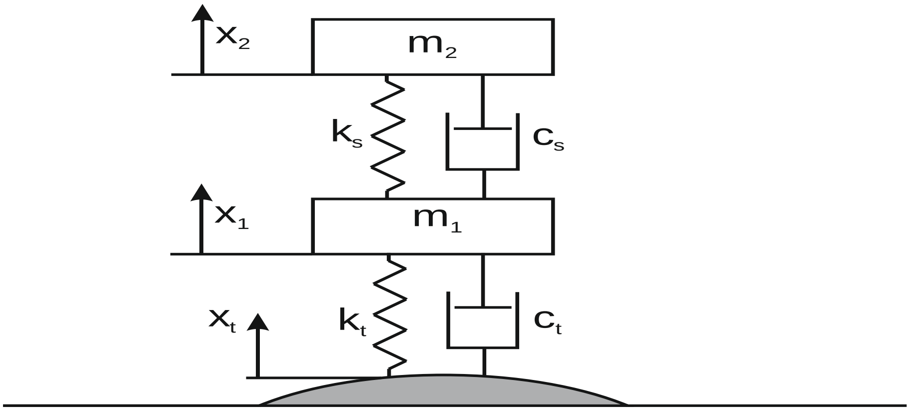

Figure 5: Passive suspension system of a quarter car model

e) Semi-active Suspension System

Fig. 6 shows the configuration of the semi-active suspension system when the vehicle is travelling over a hump. The semi-active suspension system is characterized by the presence of a controller that received the signals from the sprung mass vertical acceleration and treats them by adapting the damping coefficient of the suspension system. The equations of motion can be expressed as follow:

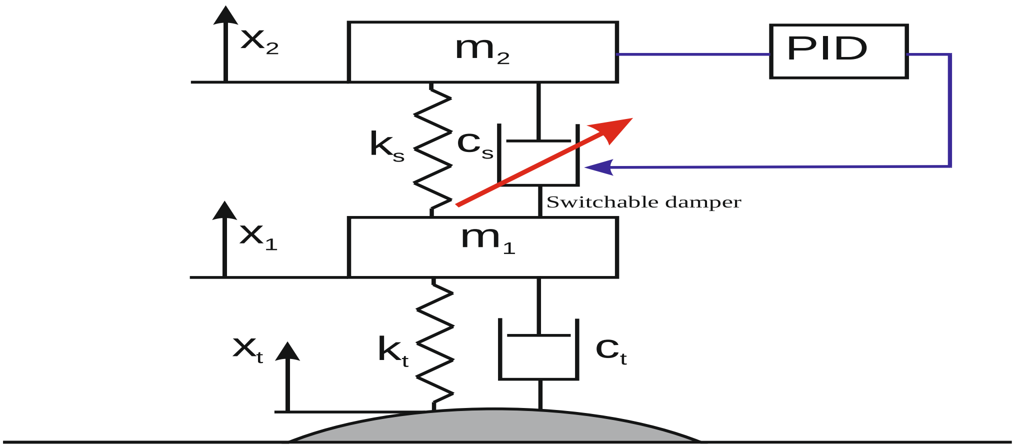

Figure 6: Semi-active suspension system of a quarter car model

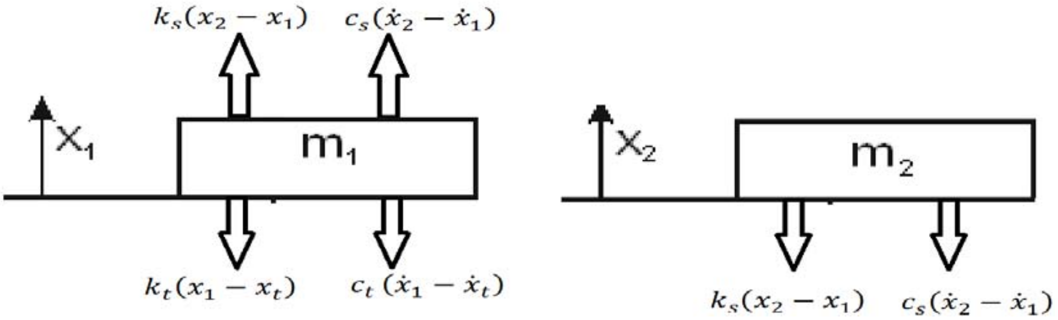

Figure 7: Free body diagram of semi-active system

For $\boldsymbol{m_1}$:

$$m_1\ddot{x}_1 = k_s(x_2 - x_1) + c_s(\dot{x}_2 - \dot{x}_1) - k_t(x_1 - x_t) - c_t\,(\dot{x}_1 - \dot{x}_t)$$
$$m_1\ddot{x}_1 + \;(c_s + c_t\,)\,\dot{x}_1 - c_s\dot{x}_2 + \;(k_s + k_t)\,x_1 - k_s x_2 = \;k_t x_t + c_t\,\dot{x}_t \tag{8}$$

For $\boldsymbol{m_2}$:

$$m_2\ddot{x}_2 = -c_s(\dot{x}_2 - \dot{x}_1) - k_s(x_2 - x_1)$$
$$m_2\ddot{x}_2 - c_s\dot{x}_1 + c_s\dot{x}_2 - k_s x_1 + k_s x_2 = 0 \tag{9}$$

Matrix Form:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_s + c_t & -c_s \\ -c_s & c_s \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_s + k_t & -k_s \\ -k_s & k_s \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} k_t x_t + c_t\,\dot{x}_t \\ 0 \end{bmatrix}$$

f) Active Suspension System

Fig. 9 shows the configuration of the active suspension system of a quarter car when the vehicle is travelling over a hump. The active suspension system is normally characterized by the presence of a linear actuator beside the suspension and the damper. The linear actuator force signals are received by the controller according to the body vertical acceleration. The equations of motion can be expressed as follow:

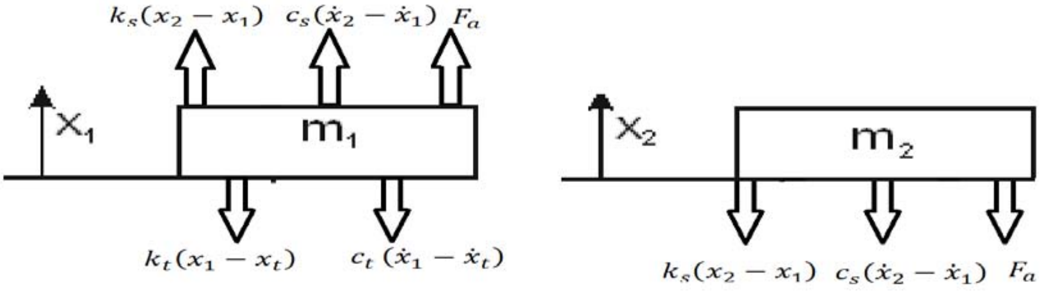

Figure 8: Free body diagram of the active system

For m_1 :

$$m_1\ddot{x}_1 = k_s(x_2 - x_1) + c_s(\dot{x}_2 - \dot{x}_1) - k_t(x_1 - x_t) - c_t\,(\dot{x}_1 - \dot{x}_t) + F_a$$
$$m_1\ddot{x}_1 + \ (c_s + c_t\,)\,\dot{x}_1 - c_s\dot{x}_2 + \ (k_s + k_t)\,x_1 - k_s x_2 = \ k_t x_t + c_t\,\dot{x}_t + F_a \tag{10}$$

For m_2:

$$m_2\ddot{x}_2 = -c_s(\dot{x}_2 - \dot{x}_1) - k_s(x_2 - x_1) - F_a$$
$$m_2\ddot{x}_2 - c_s\dot{x}_1 + c_s\dot{x}_2 - k_s x_1 + k_s x_2 = -\,F_a \tag{11}$$

Matrix Form:

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} c_s + c_t & -c_s \\ -c_s & c_s \end{bmatrix}\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} k_s + k_t & -k_s \\ -k_s & k_s \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} k_t x_t + c_t\,\dot{x}_t + F_a \\ -\,F_a \end{bmatrix}$$

Where, $\boldsymbol{F_a}$ is the actuator force.

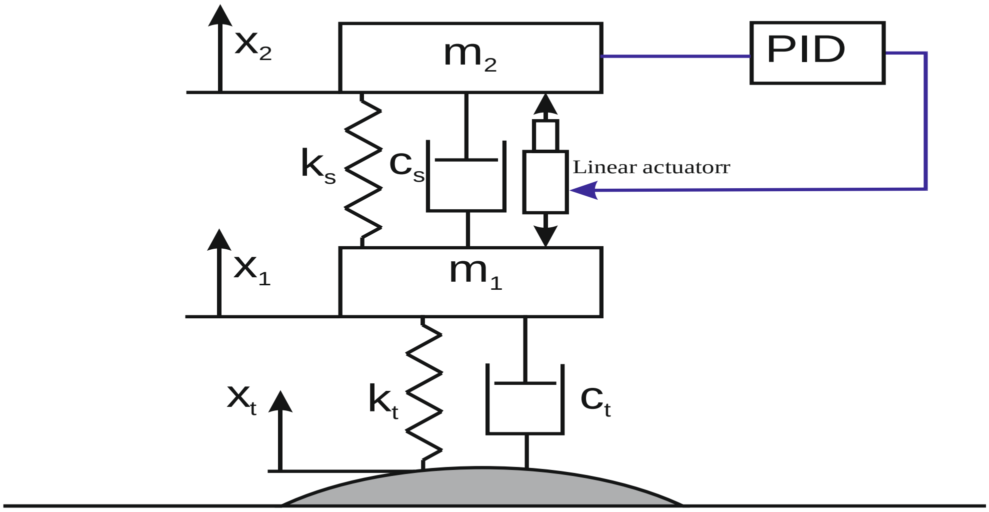

Figure 9: Active suspension system of a quarter car model

g) Output Criteria

Table 3 below shows the parameters that affect the ride comfort and the stability of the vehicle in the quarter car model and half car model, where the optimum design is to minimize the parameters as can be possible for the best ride comfort and stability.[7]

Table 3: Outputs parameter criteria

No.	Parameters / Quarter Car Model	Affect
1	Body Vertical Acceleration (m/s^2)	Ride Comfort
2	Dynamic Tire Load (N)	Stability
3	Suspensions Working Space (m)	Stability
4	Body Displacement (m)	Ride Comfort

IV. Results and Discussion

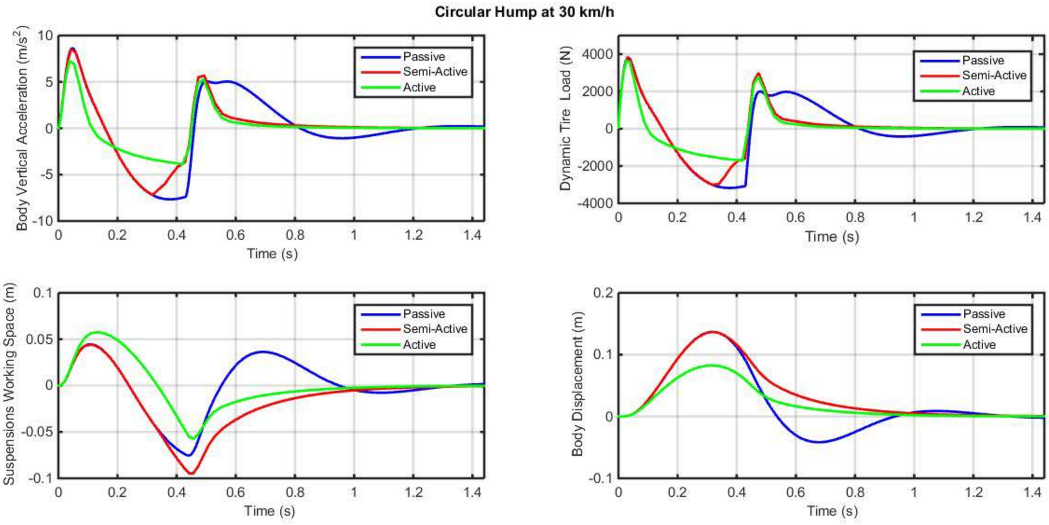

Figure 7: Vibrational behaviour of vehicle over circular hump at 30 km/h

Fig. (7) shows the dynamic vibrational behaviour of a quarter car travelling over circular hump at 30 km/h with passive, semi-active and active suspension systems. The vehicle ride comfort parameters such as body vertical acceleration and body displacement become important element especially with passive suspension system. From the other hand the body vertical acceleration is improved with semi-active while it is better for ride comfort and stability of the car when active suspension system. However, the maximum value of the body vertical acceleration is about 9 m/s^2 as a passive suspension system is used while, this value is reduced to about 6 m/s^2 as active suspension system is applied. In the same context, the suspension working space is considerably reduced as the active suspension system is applied in comparison with passive suspension system. Moreover, dynamic tire load reduced as the active suspension system is applied in comparison with passive suspension system. The body displacement of the vehicle, there is a slight improvement 0.06 m, especially when using active suspension system compared with passive suspension system.

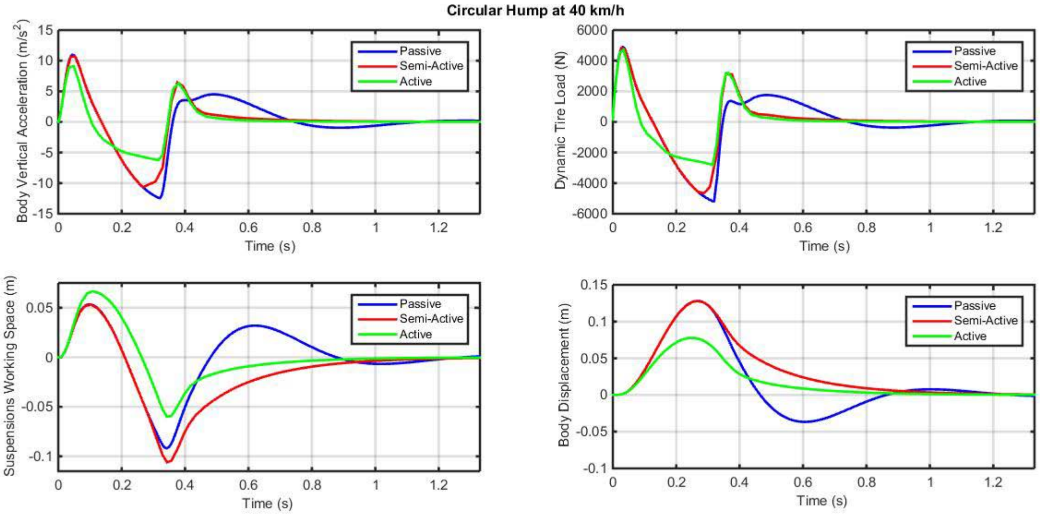

Figure 8: Vibrational behaviour of vehicle over circular hump at 40 km/h

Fig. (8) shows the dynamic vibrational behaviour of a quarter car travelling over circular hump at 40 km/h with passive, semi-active and active suspension systems. As the vehicle speed increases, the vehicle ride comfort become important element especially with passive suspension system. By using of semi active suspension system, the body vertical acceleration is improved as with semi-active suspension system. However, the maximum value of the body vertical acceleration is about 10 m/s^2 as a passive suspension system is used while, this value is reduced to about 7 m/s^2 as active suspension system is applied. In the same context, the suspension working space is considerably reduced as the semi-active suspension system is applied in comparison with passive suspension system. Moreover, dynamic tire load reduced as the semi-active suspension system is applied in comparison with passive suspension system. Looking at the body displacement of the vehicle, there is a slight improvement when using active suspension system compared with passive suspension system.

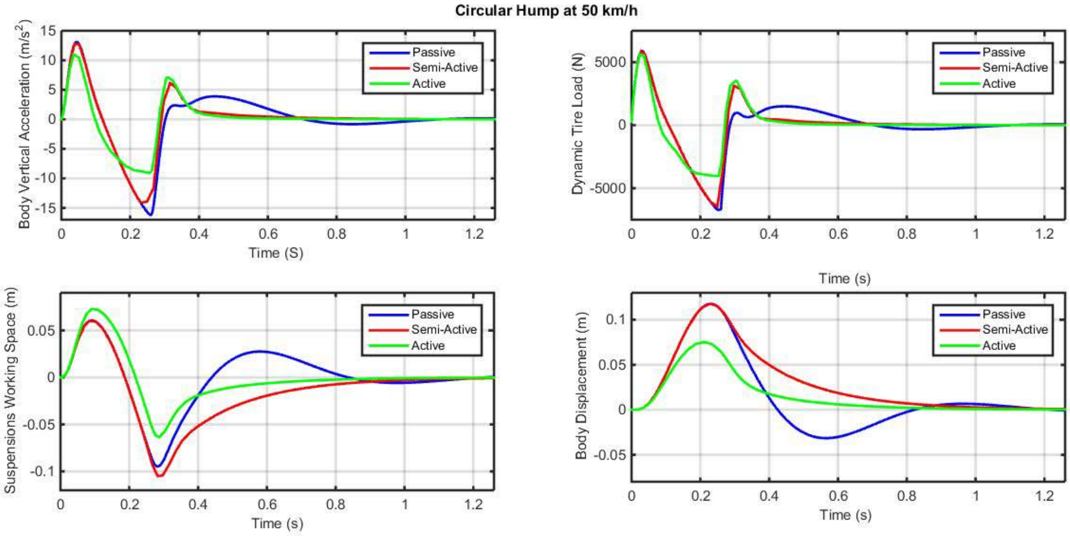

Figure 9: Vibrational behaviour of vehicle over circular hump at 50 km/h

Fig. (9) illustrates the dynamic vibrational behaviour of a quarter car that is travelling over a circular hump at 50 km/h with the passive, the semi-active and the active suspension systems. The body vertical acceleration is severely increased because of the vehicle speed is higher and hence the vehicle ride comfort is important element. The using of the semi-active suspension resulted in a slight improvement in the beginning of the hump crossing and this improvement increased at the end of the hump as a result of the controller response. By using of the active suspension resulted in a significant improvement in ride comfort compared to other suspension systems. However, the maximum value of the body vertical acceleration is about 13 m/s^2 as a passive suspension system is used while, this value is reduced to about 10 m/s^2 as active suspension system is applied. The suspension working space is considerably reduced for both suspension systems. As the semi-active suspension system is applied, a considerable reduction in suspension working space is achieved in comparison with passive suspension system. The body displacement of the vehicle, there is a slight improvement when the semi-active suspension system is used referred to the passive suspension system.

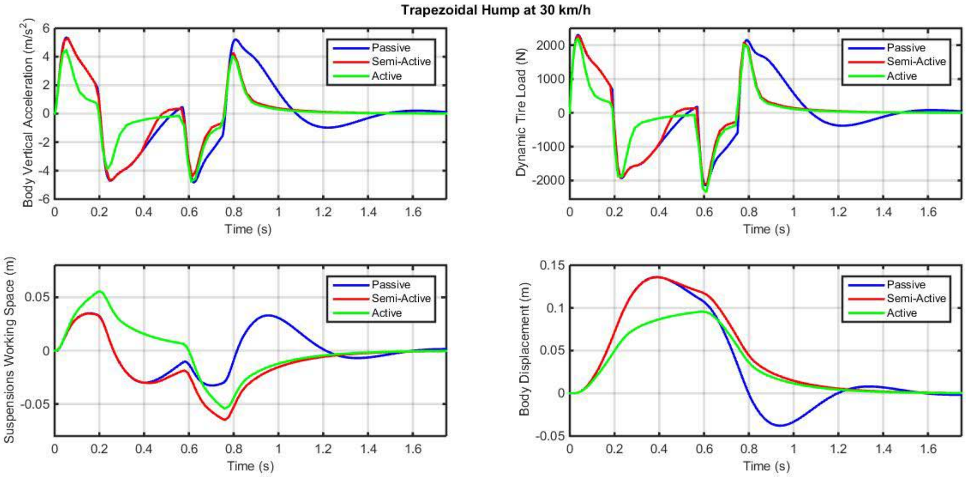

Figure 10: Vibrational behaviour of vehicle over trapezoidal hump at 30 km/h

Fig. (10) shows the dynamic vibrational behaviour of a quarter car travelling over trapezoidal hump at 30 km/h with passive, semi-active and active suspension systems. The body vertical acceleration is improved as the active suspension system is applied referred to the passive suspension system. However, the maximum value of the body vertical acceleration is about 5 m/s^2 and the body maximum deceleration is about 5 m/s^2 as the passive suspension system is used. This value is reduced to about 4 m/s^2 as active suspension system is applied. The suspension working space is considerably reduced as the active suspension system is applied in comparison with passive suspension system. No changes were prompted in dynamic tire load in both cases. The body displacement of the vehicle is slightly improved with the active suspension system compared with the passive one.

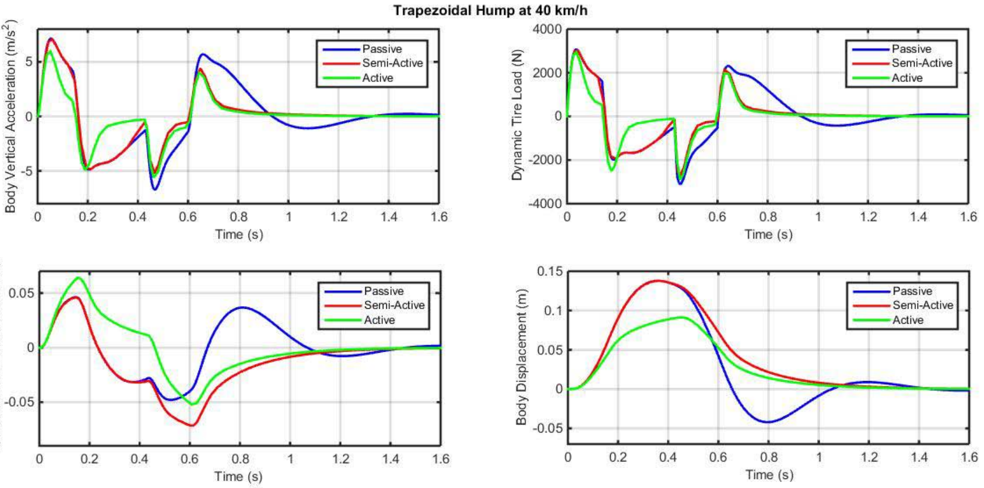

Figure 11: Vibrational behaviour of vehicle over trapezoidal hump at 40 km/h

Fig. (11) shows the vibrational behaviour of a quarter car that is travelling over trapezoidalhump at 40 km/h vehicle speed using passive, semi-active, and active suspension systems. The body vertical acceleration is recorded at high levels especially with passive suspension system and it is considerably reduced as semi-active as well as active suspension systems are applied. However, the maximum value of the body vertical acceleration is about 8 m/s^2 with a passive suspension system and is reduced to about 6 m/s^2 with the active suspension system. In the same context, the suspension working space is considerably reduced as the active suspension system is applied in comparison with the passive suspension system. Ignored changes were prompted in dynamic tire load in semi-active suspension system related to the passive suspension system. However, there are slightly reductions in dynamic tire load with the active suspension system. The body displacement of the vehicle is severely affected by the travelling over the hump with the passive and the semi active suspension system. This effect was less in the case of active suspension.

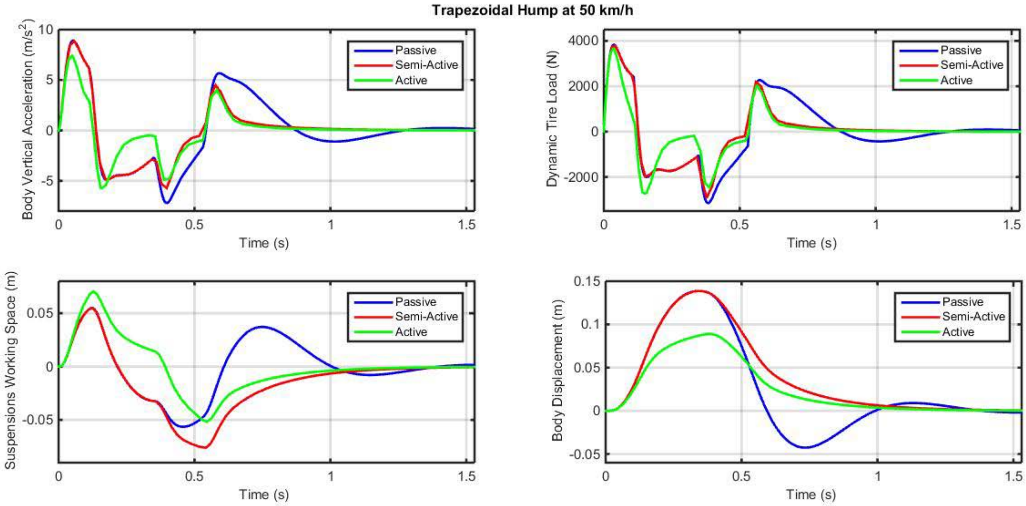

Figure 12: Vibrational behaviour of vehicle over trapezoidalhump at 50 km/h

Fig. (12) shows the dynamic vibrational behaviour of a quarter car travelling over trapezoidal hump at 50 km/h with the passive, the semi-active and the active suspension systems. The body vertical acceleration is improved as with active suspension system is used referred to the passive one. However, the maximum value of the body vertical acceleration is about 9 m/s^2 as a passive suspension system is used while, this value is reduced to about 7 m/s^2 as active suspension system is applied. The suspension working space is considerably reduced as the semi-active suspension system is applied in comparison with active suspension system. The dynamic tire load is slightly improved with the active and semi active suspension systems referred to the passive one. The body displacement of the vehicle is considerably improved with the active and the semi-active suspension systems referred to the passive one.

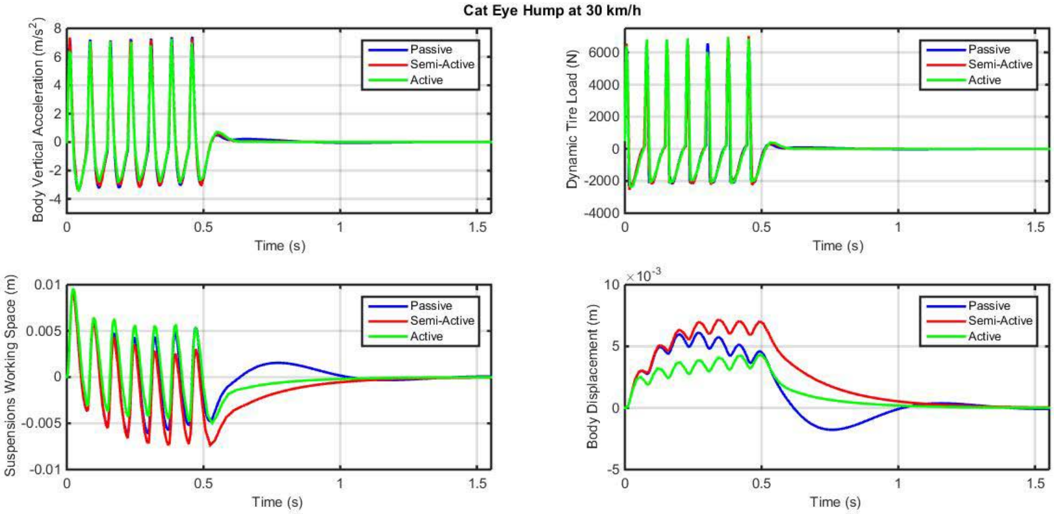

Figure 13: Vibrational behaviour of vehicle over cat-eyehump at 30 km/h

Fig. (13) shows the dynamic vibrational behaviour of a quarter car travelling over cat-eyehump at 30 km/h with passive. semi-active and active suspension systems. The vehicle ride comfort is worthily affected as the vehicle travelling over the cat eye hump at 30 km/h. No considerable changes in the body vertical acceleration were achieved with the using of the active and the semi-active suspension systems related to the passive one. However, the maximum value of the body vertical acceleration is about 7 m/s^2 as a passive suspension system is used while, this value is reduced to about 6 m/s^2 as active suspension system is applied. In the same context, the suspension working space is slightly reduced as the active suspension system is applied in comparison with passive suspension system. Differently, no change was prompted in dynamic tire load in both cases. The body displacement of the vehicle is considerably reduced as the using active or semi-active suspension systems compared with the passive suspension system.

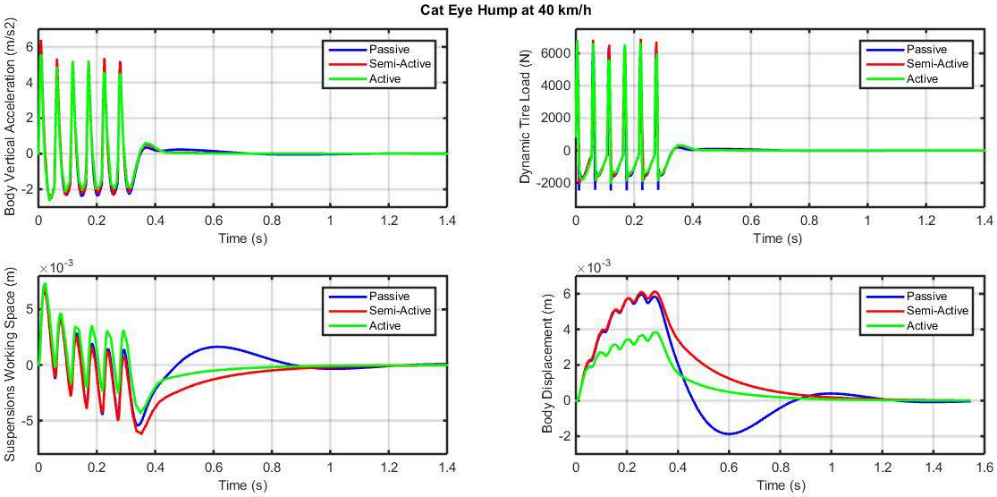

Figure 14: Vibrational behaviour of vehicle over cat-eyehump at 40 km/h

Fig. (14) shows the dynamic vibrational behaviour of a quarter car travelling over cat-eyehump at 40 km/h with the passive, the semi-active and the active suspension systems. As the vehicle speed is increased from 30 km/h to 40 km/h, the body vertical acceleration is reduced to about 5 m/s^2 referred to 30 km/h vehicle speed there is no change prompted in. However, the maximum value of the body vertical acceleration is about 7 m/s^2 as a passive suspension system is used while, this value is reduced to about 5 m/s^2 as active suspension system is applied. In the same context, the suspension working space is considerably reduced as the active suspension system is applied in comparison with passive suspension system. Differently, no change was prompted in dynamic tire load in both cases. Looking at the body displacement of the vehicle, there is a slight improvement when using active suspension system compared with passive suspension system.

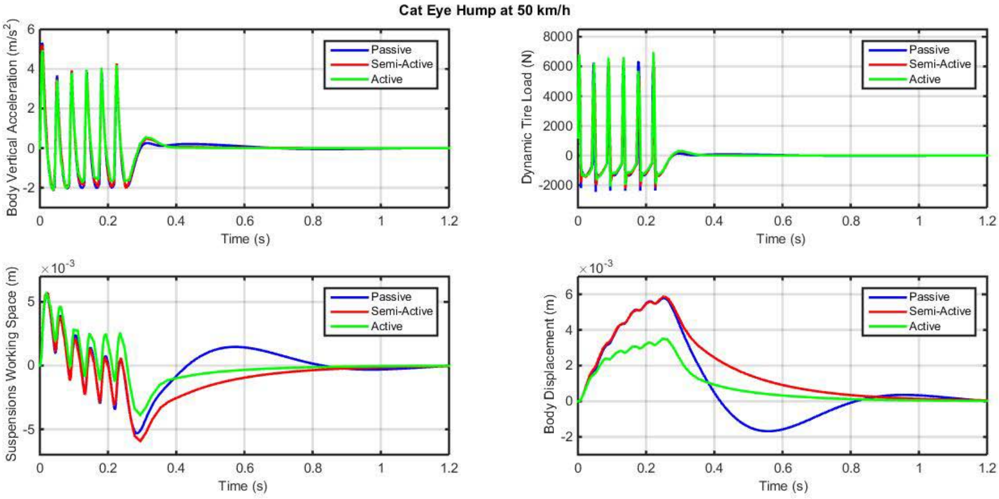

Figure15: Vibrational behaviour of vehicle over cat-eyehump at 50 km/h

Fig. (15) shows the dynamic vibrational behaviour of a quarter car travelling over cat-eyehump at 50 km/h with passive. semi-active and active suspension systems. The body vertical acceleration are improved as the vehicle speed increased. There are no tangible changes prompted in the body vertical acceleration when the semi-active or the active suspension system are used. However, the maximum value of the body vertical acceleration is about 4m/s^2 as a passive suspension system is used while, this value is reduced to about 3.8 m/s^2 as active suspension system is applied. In the same context, the suspension working space is slightly reduced as the active suspension system is applied in comparison with passive suspension system. Differently, no change was prompted in dynamic tire load in both cases. Looking at the body displacement of the vehicle, there is a slight improvement when using active suspension system compared with passive suspension system.

V. CONCLUSIONS

The following conclusions can be achieved:

- Mathematical models were introduced to study the vibrational behaviour of the vehicle when traveling over various types of road humps such as the circular, the trapezoidal and the cat-eye humps, using a passive, a semi-active and an active suspension systems.
- The parameters that were investigated in this study to evaluate the ride comfort are the body vertical acceleration, the suspension working space, the dynamic tire load and the displacement of the body.
- The ride comfort is greatly affected by driving over humps, especially at high speeds.
- Traveling over humps, whether circular or trapezoidal, has a great impact on the comfort of riding, as well as the stability of the car.
- There is a clear and tangible improvement when a semi-active suspension system is used compared to a passive suspension system. The semi-active suspension system is characterized by the presence of PID controller. The PID goal is to minimize the value of the body vertical acceleration values considering the body vertical acceleration as the controller input and changing the damping coefficient as the controller output.
- These improvements were obtained in the body vertical acceleration, the suspension working space, the displacement of the body, and the dynamic tire load levels.
- With the high speeds, the ride comfort is achieved for all the humps used in this study except for cat-eye hump, whereas the worth ride comfort is achieved at low speeds.
- Therefore, through these results, it can be recommended to use the active or semi-active suspension systems instead of the passive

suspension system to improve ride comfort and maintain the car's stability while the vehicle is traveling on humps.

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